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De l'Espace pour la Terre

The 3MI mission

for operational monitoring of aerosols from EPS-SG

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REPORT FROM:

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Executive summary

Because of their interaction with radiation, clouds and precipitation, aerosols are key elements for the radiative budget of the Earth and critical pieces of uncertainty in climate change prediction and assessment of feedbacks.

Given their high variability in time and space satellite remote sensing is the only means to monitor their day to day evolution.

In the two last decades more and more sophisticated observations have become available and significant progress has been achieved in the inversion of aerosol properties. Still, the level of accuracy and characterization expected by the users is not achieved yet. Better and similar quality over land and ocean, not achieved at present, as well as characterization of the aerosol absorption properties and vertical profile are required in near real time for assimilation in the models.

The wealth of A-train observations has allowed in-depth analysis and understanding of the respective instruments and algorithms merits. Especially the spectral, directional and polarization capabilities are now clearly understood as independent pieces of information driving the level of characterization that can be achieved from the measurements.

Whereas over past years, the ability of sensors to fulfil the dimensional space of information has increased significantly till now, only “MODIS class” conventional spectral imagers designed for meteorological purposes are currently planned beyond the A-train era. They have limited performance, especially over land where applications are more demanding.

Alternative approaches exploring the **Multi-directional, Multi-polarization and Multispectral (3M)** space have been successfully implemented. Among those, the most complete to date has been provided by POLDER. Pioneering polarization for Earth observation since 1996, the POLDER-1, POLDER-2 and PARASOL missions have now fully demonstrated that polarization, owing to its sensitivity to particle shape, is a clever solution for constraining the aerosol/surface ill-posed inversion.

Improvements to the original POLDER specifications expanding the present capabilities along the spectral and resolution dimensions are proposed for the 3MI instrument

Polarization in the SWIR will provide access to the aerosol coarse particles over land and allow the complete characterization of the aerosol size distribution with total, fine, coarse, spherical and non spherical fractions. Combined with a second generation of algorithms essential missing parameters such as aerosol absorption and altitude will become available with 3MI. This level of characterization is out of scope for spectral radiometers.

The POLDER instrument concept is proven, simple, light and reliable. Industrial studies performed by CNES and ESA have shown that going from POLDER to 3MI does not require to change the instrument concept, thus allowing 3MI to remain a light instrument with strong technical heritage limiting the development risks.

Implementation of 3MI on EPS-SG would provide both the adequate long term prospect and the NRT operational delivery to users of a full suite of aerosol products for developing their operational applications and contributing to unravel the climate puzzle. EPS-SG is also the opportunity for developing a high level of synergy between 3MI and MetImage, UV-NS, IASI-NG and CERES which will further increase the benefit from 3MI alone.

Capitalizing on European heritage and skills, flying 3MI on EPS-SG would give Europe leadership in aerosol remote sensing for the next 20 years.

Introduction

When the current generation polar meteorological satellites were designed in the 90's, the role of aerosols on meteorology and climate was far from being assessed and monitoring air quality from satellite was just an emerging possibility. Since then and thanks to a number of scientific missions (especially the A-train) and progress in modelling, the importance of aerosol monitoring on the long term has been clearly demonstrated.

The aim of this document is to support the 3MI instrument as an aerosol dedicated instrument onboard EPS-SG as a unique opportunity to meet a number of scientific goals from the meteorological and climate communities.

We first review the user needs for operational aerosol products for climate, numerical weather prediction (NWP), air quality (AQ) and interest manifested by other instruments for atmospheric correction purposes.

Then we face these user requirements to the aerosol remote sensing capabilities in terms of parameters and performances, from the past to the present and derive future needs from this overview.

Looking carefully at the different sensors and analysing their respective characteristics allows us to propose a categorization by observations capabilities (spectral, directional, polarization, resolution and coverage). The respective merits of each are highlighted. The **Multi-spectral Multi-directional Multi-polarization (3M)** concept is presented and illustrated with POLDER/Parasol results.

Finally an advanced 3MI instrument is proposed to fill the lack of aerosol sensors in the mid to long term. The benefits from flying 3MI on EPS-SG are highlighted.

1 Operational needs for aerosols

1.1 Needs for operational aerosol forecasting

The European MACC (Monitoring Atmospheric Composition and Climate) project, coordinated by ECMWF (European Centre for Medium-Range Weather Forecasts), has developed a global aerosol monitoring and forecasting service to support institutions that are providing advice and warnings related to atmospheric composition. In its pre-operational configuration, MACC routinely produces analyses and forecasts of various species of aerosols. Significant events such as the Australian dust storm over Sydney in October 2009, the Eyjafjallajökull volcanic eruption in April 2010 or Russian fire plumes in August 2010, have been well analysed and forecast by the MACC system, illustrating its great potential in terms of air quality monitoring and forecasting.

The pre-operational forecasting of aerosols in MACC has already a number of users:

- institutions responsible for producing air quality forecasts require boundary conditions for their forecast that can only come from a global aerosol model, thus requiring in turn a global satellite product,
- the solar industry requires aerosol forecast to predict the amount of solar energy that can be produced and sold on the market. There is a need for improved information on aerosol size distribution over land in addition to standard parameters such as AOD (Aerosol Optical Depth).

- An improved UV index has been developed which includes not only the effects of ozone and clouds, but also aerosols.
- the WMO (World Meteorological Organization) Sand and Dust Storm forecasting centres rely on aerosol forecasts for their warning system.

Continuation of the MACC project as the GMES Atmospheric Service requires a continuous input of satellite aerosol information from space. Improvement in the service will require improvement in the aerosol model, the data assimilation procedure and the aerosol satellite data. For instance aerosol fine mode AOD from the MODIS instrument is currently assimilated but gives limited benefit over land. We anticipate that progress in assimilating aerosol information in models will be limited by the accuracy and information content of the satellite data should there not be a step increase in the capability of operational satellite radiometers.

In particular the model analysis in MACC would benefit from improved products over land, less contamination by clouds or sea foam, some aerosol speciation (in particular through characterization of the single scattering albedo) and better characterisation of the retrieval error. It is very unlikely that standard spectrometers can provide all the required information over land despite anticipated progress in aerosol algorithms. Spectrometers with multidirectional and polarization capability have the potential to provide such aerosol information as recent progress in aerosol algorithm has demonstrated (e.g. Waquet et al., 2010 ; Dubovik et al., 2011).

The Volcanic Ash Advisory Centres (VAACs) would strongly benefit from an enhanced operational capability to measure aerosols from space. The grounding of most aircraft in Europe during the Eyjafjallajökull eruption has caused some significant changes in the aviation industry and to the way the VAACs should respond to such events in the future. Air traffic control now requires the provision of charts with three levels of ash concentration. Moreover air traffic control may authorise airlines to fly in any zone as long as they have approved safety procedures in place. This requires the VAACs to predict ash concentrations rather than just no-fly zones. In the absence of reliable information on the volcanic ash source term, model predictions need to be constrained by space observations. Ideally such observations should come from geostationary orbit, but the capability of geostationary satellites to measure aerosol properties is much less than that of some instruments on polar-orbiting satellites. Also for the case of Icelandic volcanoes, geostationary satellites only offer a very slanted view, which makes aerosol retrievals difficult. There is therefore a strong advantage for an operational polar-orbiting capability in ash measurements. Relevant aerosol quantities, beyond AOD, are some information on the plume altitude, aerosol size distribution, and absorption (to improve the accuracy on the AOD retrieval). While IR spectrometers such as IASI can provide most of the required information on ash, including an estimate of the plume altitude, a radiometer operating in the UV and visible spectrum could be a useful add-on to characterize the smaller ash particles, which are transported further away than the larger particles.

1.2 Needs for aerosol monitoring for climate

The aerosols characteristics (optical thickness and other parameters) are one among the Essential Climate Variables identified by the Global Change Observing System [GCOS report, 2006].

Indeed aerosol monitoring is particularly important in relation to climate research on most

timescales. Anthropogenic aerosols are responsible for a radiative forcing through their direct and indirect effects on radiation and clouds. The aerosol radiative forcing over the industrial period remains very uncertain and this is a major cause as to why the climate sensitivity cannot be constrained from past observations of the surface temperature record.
Improved characterisation of aerosol properties, such as enabled by the 3MI instrument, are therefore key to progress in understanding long-term climate change. In particular, the remaining uncertainties concentrate on aerosol loadings and properties over land, including their degree of absorption. It has been shown that aerosol absorption above cloud could contribute to a significant positive radiative forcing. Only with satellite instruments with a capability to measure aerosol absorption (in clear sky and above clouds) can progress be made in quantifying and monitoring the aerosol direct effect.

Operational monitoring of aerosols (which in the MACC project comes at no additional cost to operational forecasting) is also critical to recent developments in climate services on the seasonal to decadal timescales. It is known that aerosols can show large amounts of interannual variability (especially in regions of biomass burning and dust production) which may affect the seasonal climate. Thus, it is therefore likely that seasonal forecasts in the future will include predictions for aerosols to satisfy user needs in that respect. Aerosol monitoring from space will be required to verify and initialize such forecasts. Decadal forecasting is also a field that is moving from research into operations as some skill has been demonstrated. On such timescale, the predictability is coming from the existence of low frequency modes of variability in the climate system, as well as changes in anthropogenic radiative forcings such as greenhouse gases and aerosols.

The aerosol forcing has a strong regional component which can change rapidly in response to air quality policies and changes in the land surface. It is critical to monitor changes in the aerosol radiative forcing at the regional scale in order to be able to make the best possible use of sources of predictability in decadal forecasting. The MACC project already has a pre-operational monitoring of the aerosol forcing which would benefit greatly from 3MI measurements.

3MI on EPS-SG, thanks to the time frame of the EPS-SG programme and the possibility of further extension, will allow to address the long term trend issue for aerosols. 3MI will also deliver parameters which will allow to better understand the role of aerosols in climate and improve/validate the physics of the models. 3MI products will be used as input in assimilation or initialization of seasonal/decadal models. At the bottom line, it should contribute to the detection or even attribution of any climate change impact.

1.3 Needs for numerical weather prediction

Until recently, the representation of aerosols in Numerical Weather Prediction (NWP) models and associated data assimilation schemes has been very crude, often in terms of climatologies.

Although the MACC above-mentioned project can be considered as a pioneering project with a dedicated mission, there is no doubt that the development of its capabilities at representing aerosols paves the way towards what will become possible to achieve in NWP in the decade to come. In the recently approved ECMWF 10 year strategy, it is explicitly mentioned that the components of the extended IFS (Integrated Forecasting System) that assimilate and forecast atmospheric composition will continue to be developed and enhanced and will gradually be integrated into ECMWF's core weather forecasting applications. For example, the analysed aerosols from MACC will be used instead of an aerosol climatology in assimilation and core forecasting applications, and progressively interactive aerosols will be introduced in the time frame of EPS-SG. Other meteorological centres follow a similar development path.

A better representation of aerosols in NWP models will lead not only to an improved aerosol forecasting capability, but also enhanced quality of weather parameters such as visibility, 2m temperature (both parameters which have an increasing societal impact), improved clouds and precipitation (via a better representation of the interaction between aerosols and clouds), etc.

Several facets for the use of aerosol observations for NWP have to be considered:

- As aerosols become prognostic variables in the model, they need to be analysed with the highest possible accuracy. Today, MACC assimilates aerosol optical depth measurements at 550 nm from the MODIS instrument, to which the fine mode at the same wavelength will soon be added. The extension to the assimilation at several wavelengths is underway and will become routine by the time of EPS-SG. Work is also underway to develop an assimilation capability of CALIPSO (and later EARTHCARE) backscatter coefficient profiles.

- Another immediate benefit of better aerosol information in NWP concerns the use of satellite radiances in data assimilation scheme. We can demonstrate today the extreme sensitivity of satellite instruments such as AIRS and IASI (and therefore IASI-NG in the future) to aerosol and gas emissions which can produce a small, but significant disturbance of infrared spectral measurements. To prevent these disturbances being misinterpreted as erroneous temperature information, it is important to detect and reject situations where the radiance observations are believed to be strongly contaminated by aerosols. At ECMWF, a scheme has been developed that is dedicated to the identification of clouds and aerosol signatures in AIRS and IASI observations. This scheme, which for the time being solely relies on the instruments themselves, would benefit from having collocated independent aerosol information that could be provided by a 3MI type instrument.

- The concern shared among the atmospheric composition community about the foreseen poor aerosol observation capability at the horizon 2020+ (no dedicated operational mission from the US, forthcoming end of EOS, difficulty to converge on a common land and ocean product with GMES Sentinel 3 for which the aerosol capability was not sought at first, etc.) is likely to be shared by the NWP community as its capability expands and capitalises on the MACC developments

- The requirements from global NWP in terms of aerosol observations are obviously for real time access, and for global and geographically homogeneous products.

1.4 Needs for Air Quality monitoring and forecasting

Aerosol is one of the key pollutants affecting human health. Epidemiologic surveys have indicated a clear link between exposure to aerosol and morbidity/mortality. Up-to-date information can for instance be found on the Aphekom project website (http://www.aphekom.org); exceeding WHO (World Health Organisation) Air Quality Guidelines on PM2.5 in 25 European cities with 39 million inhabitants results annually in 19000 deaths (15000 of them from cardiovascular diseases) and €31.5 billion in health and related costs. European directives, national laws as well as local regulations have been set up on fine particulate matter mass concentrations, in order to inform and protect European citizens. While anthropogenic emissions abatement is a key objective, monitoring and short- to medium-term forecasting aerosol concentration levels (PM10, PM2.5, increasingly PM1) is very important for informing citizens and for possibly taking temporary emissions control measures in order to reduce exposure. Beyond mass concentration, particle size appears to be also a key factor regarding health impact, with smaller particles having the most deleterious effects regarding respiratory and cardiopulmonary diseases.

The aerosol levels found at a given place not only depends on local emissions and local meteorology, but also on larger-scale transport of polluted air masses. The current operational observing system for air quality is mainly based upon surface sites, which are in general located in high-density population areas. While this set-up allows to achieve the objective of monitoring exposure of people, this provides only a weak constraint for assimilation in the Air Quality forecast models that are used today (see for instance: http://macc-raq.gmes-atmosphere.eu/ or http://www.prevair.org). Not only the spatial representativeness of surface measurements sites is often inadequate for national or regional-scale models, but also the observing system is essentially blind regarding polluted air masses aloft, that can be entrained down to the surface with the diurnal evolution of the Planetary Boundary Layer (PBL). Even though current models have some skill in forecasting PM10 and PM2.5, the relative skill is significantly worse than for gas phase pollutants, like nitrogen oxides or ozone. In particular, models tend to underestimate systematically surface aerosol concentrations and the reasons for this are not fully understood, lying probably upon our lack of knowledge on both emissions and chemical/thermodynamic processes. Adding information on the above surface aerosol mass and size characteristics is certainly a key need for improving on today's Air Quality forecast capabilities and on the quantification of the long-range contribution to aerosol concentrations. This need is obviously mainly over land surfaces where most emissions take place, but aerosol observations over oceans are also of importance for studying transport onto coastal cities and to get insight on the physical and chemical ageing of aerosols.

With the spatial coverage it offers, satellite remote-sensing of aerosol properties is a key sector for filling the gap in the current aerosol observing system. However, different aerosol properties impact on the signal: mass, size, chemical composition and vertical distributions. Even if some satisfactory results have been obtained using AOT in order to derive PM2.5, strong assumptions are needed regarding the types of aerosol and their vertical distributions. Attempts made with POLDER and CALIPSO data are certainly leading a promising path in this regard of disentangling the various aerosol characteristics. Another challenge is that Air Quality applications require information on the temporal evolution of aerosol. Indeed emission sources, as well as meteorological parameters (PBL height, winds, rainfall...) that affect aerosol distribution, vary on short timescales and it is needed to have high-frequency information, up to the order of one hour. This type of requirement is met by instruments on GEO orbit, but as MSG/SEVIRI or its successor on-board MTG, instruments on this orbit cannot provide the needed unambiguous information on the aerosol properties. Major advances are thus to be expected from the synergy between 3MI on LEO and GEO instruments: the broad picture is that the LEO/3MI information will allow updating aerosol characteristics, while model and GEO observations allow extrapolating in time and space between two LEO overpasses. In this regard, 3MI can be seen as a key value-adding and cost-effective additional instrument for making full use of the high-frequency aerosol signal available with GEO instruments.

Air quality forecast applications are now operational in several European countries, serving as a basis for decision taking. The requirement regarding timeliness is thus real-time access, very much like for NWP applications. The data assimilation systems currently generally use level 2 information, but it is expected that within the few coming years developments on observations operator will generalise and allow direct assimilation of level 1b data.

1.5 Unique synergies with companion payload instruments

The four optical instruments of EPS-SG - MetImage, IRS, UVNS and 3MI - are highly complementary, and constitute an optimal synergistic combination to perform monitoring of the atmosphere for NWP, nowcasting, climate, and atmospheric chemistry applications. The synergy exists in two ways: the ***retrieval*** of atmospheric composition and clouds, and the ***use*** of the retrieved data in application fields.

Synergy in retrieval

The unique aspects of 3MI which provides detailed aerosol information, multi-directionality of radiances and polarisation, can be combined with the high resolution imagery of MetImage and the spectrometry of IRS and UVNS in many ways; a few examples of possible synergy are given here:

- The aerosol information that is delivered by 3MI helps in the retrieval of atmospheric trace gases from the spectrometers IRS and UVNS, since aerosols affect the light path and therefore affect the detected trace gas columns. This is especially relevant for trace gases in the UVNS spectral range . Leitão et al (2010) showed that to improve current tropospheric NO_2 retrieval w.r.t. aerosol, a better knowledge to the aerosol vertical distribution, AOD, SSA (single scattering albedo) and ideally coarse and fine mode aerosol size distribution is required. This needs to be accompanied by a better knowledge of the surface albedo. Similar is applicable to other reactive or non-reactive trace gases in the troposphere.
- The polarisation information from 3MI will help to correct for remaining polarisation sensitivities in the UVNS and MetImage instruments.
- The polarisation information from 3MI will help to correct for remaining polarisation sensitivities in the UVNS and MetImage instruments.
- The multi-directionality and polarisation of 3MI helps to interpret the single view data of MetImage in case of cirrus clouds, aerosols above clouds, and volcanic ash plumes.
- The multi-directionality measurements by 3MI enable to determine SW (short wave) radiant fluxes from MetImage, which has many spectral bands covering the solar range. This will contribute to monitoring and understanding aerosol radiative forcing.
- The O_2 A-band cloud pressure from 3MI is complementary to the cloud height from MetImage which is based on the thermal infrared. It will help to detect multilayer clouds and warm clouds in MetImage imagery.
- The high-spatial resolution cloud information from MetImage will help to improve 3MI aerosol products by detecting subpixels clouds.
- The UV channels of Metimage will also help to enhance the absorbing aerosol information from 3MI.
- The UVNS spectrometer covers same wavelength range as the 3MI, but at higher spectral resolution. This will help to spectrally calibrate the 3MI channels, e.g. the O_2 A-band channels.
- Synergy in radiometric calibration between 3MI and MetImage and UVNS.

Synergy in data usage applications

Aerosols play an essential role in many physical and chemical processes in the atmosphere, for example cloud formation, radiative processes, and chemical cycles. The contribution of 3MI on EPS-SG is to measure aerosols at the same locations and times where the clouds and trace gases are measured.

Aerosols have their primary emission sources at the surface, where also trace gases are emitted, e.g. from industrial activities, energy production, road traffic and shipping. Secondary sources of aerosols are due to chemical reactions between trace gases. To understand the sources of aerosols and their chemical composition, simultaneous measurements of aerosols and trace gases are required. This can be achieved with the EPS-SG mission, having 3MI together with IRS and UVNS on board.

The relationship between emissions of aerosols and trace gases was studied recently by Veefkind et al. (2011). They used MODIS AOT and OMI trace gas columns to study aerosol formation and chemical composition. They found that the ratio of AOT to tropospheric NO_2 is different for different parts of the globe [Fig.1,2]. This dependence is related to the sources of aerosols and NO_2. For example, if the source of NO_2 and aerosols is fossil fuel burning, then the ratio AOT/NO_2 indicates the inefficiency of the combustion process. The relationship of the AOT from 3MI with NO_2 and other gases, like SO_2, HCHO, CO, and NH_3, that will be detected by UVNS and IRS, will contribute strongly to understanding aerosol sources and composition from the EPS-SG mission.

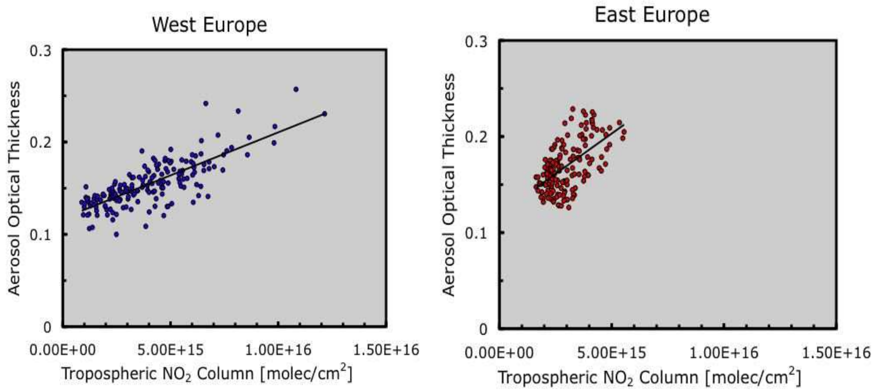


Fig.1 Relationship between aerosol optical thickness from MODIS and tropospheric NO2 from OMI for Western and Eastern Europe, indicating different fuel sources and combustion processes (Veefkind et al., 2011).

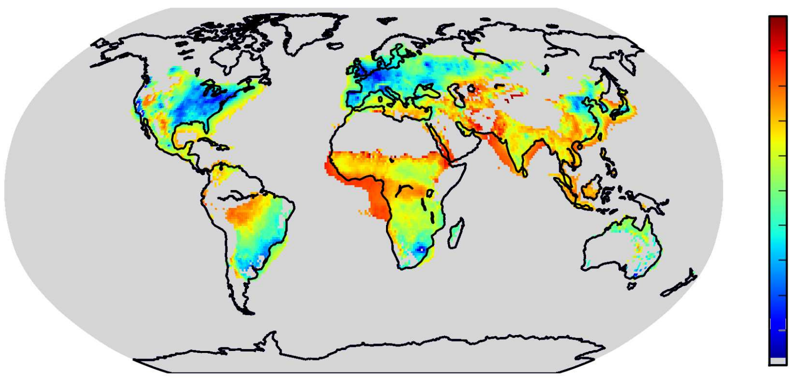


Fig. 2. Global map of the ratio AOT/NO_2 from MODIS and OMI. Red means high ratio, blue means low ratio. The AOT/NO_2 ratio shows differences in aerosol sources and combustion efficiencies (Veefkind et al., 2011).

2 Aerosol remote sensing from space

The best strategy for characterizing aerosols and estimating their radiative forcing is to integrate measurements from satellite sensors with in-situ and surface based measurements.

As illustrated by animations of current satellite products satellite remote sensing from space is the only means of characterizing the large spatial and temporal variability of aerosols while in-situ can bring more detailed and accurate description of chemical composition, microphysical or optical properties.

After reviewing the user needs in §1, we now consider the space remote sensing capabilities at present and in the future.

2.1 Overview of missions/sensors capabilities in terms of aerosol characterization so far

The following table, adapted from the AAP and climate Impact 1999 report and completed with ESA sensors, gives an interesting perspective to missions/sensors capabilities in terms of aerosol characterization.

Category	Properties	Parameters	Spatial coverage	Sensor/PF	Temporal coverage
Column Integrated	Loading	AOD 640nm	~daily coverage Ocean	AVHRR series	1981-
		AOD 380nm	~daily coverage Ocean & Land	TOMS/Nimbus, ADEOS, EP	1979-2001
		AOD 550nm	~half-weekly cov. cov Ocean & Land	A(A)TSR/Envisat	Apr 1995-
		AOD 865nm	~daily coverage Ocean & Land no glint	POLDER 1,2 PARASOL	1996, 2003 Dec 2004-
		AOD 500nm	~daily coverage Ocean glint (Land)	MERIS/Envisat	March 2002-
		AOD 550nm	~daily coverage Ocean & Land	MODIS/Terra MODIS/Aqua	Mars 2000- May 2002-
		AOD 550nm	~weekly Ocean & Land bright surf, no glint	MISR/Terra	2000-
		AOD 380nm (AOD 500nm)	~daily coverage Ocean & Land	OMI/Aura	Jul 2004-
		AOD 640nm	GEO (hourly cov.) Atlantic Europe, Africa	SEVIRI/MSG Meteosat 8,9	Aug 2002 Dec 2005
		Angström exp 640nm / 840nm	~daily coverage Ocean	AVHRR series	1981-

	Size & Shape	Angström exp	~half-weekly cov Ocean & Land	A(A)TSR/Envisat	Apr 1995-
		Fine mode fraction Angström exp 670nm / 865nm Non spherical fract	~daily coverage Ocean & Land	POLDER 1,2 PARASOL	1996, 2003 Dec 2004-
		Angström exp	~daily coverage Ocean large glint	MERIS/Envisat	March 2002-
		Fine mode fraction Angström exp Effective radius Asymmetry factor	~daily coverage Ocean	MODIS/Terra, MODIS/Aqua	2000- May 2002-
		Angström exp Small, med, large, non sph fractions	~weekly Ocean & Land Bright surf, no glint	MISR/Terra	2000-
		Angström exp	GEO (hourly) Atlantic EU, Africa Ocean (Land)	SEVIRI/MSG Meteosat 8,9	Aug 2002 Dec 2005
	Absorption	AI (aerosol index) SSA 380nm absAOD 380nm	~daily coverage Ocean & Land	TOMS/Nimbus, ADEOS, EP	1979-2001
		AI (aerosol index) SSA 500nm abs AOD 500nm		OMI/Aura	Jul 2004-
		SSA 550nm (2-4 bins)		MISR/Terra	2000-
Vertical-resolved	**Loading Size Shape**	Extinction to back-scatter ratio 532nm	Global Ocean & land 16-day cycle single nadir obs.	GLAS/IceSAT	2003 3 months
		Extinction to back-scatter ratio 532nm color ratio depolarization		CALIOP/CALIPSO	2006-

Table 1 : Summary of major satellite measurements currently available for aerosol monitoring (adapted from the AAP and climate Impact 99 report)

One can see that aerosol remote sensing is a relatively recent field with dedicated aerosol instruments only available since the late 90s. But over the past decade enormous progress has been made, thanks both to more sophisticated instruments on one hand and retrieval algorithms on the other. Better spatial resolution, more parameters and better accuracy can be achieved nowadays. However, the level of aerosol speciation with the discrimination between natural aerosol and anthropogenic aerosol as requested by the users has not been reached yet.

All missions provide total aerosol optical depth (AOD) as a proxy for aerosol loading and almost all provide in addition a spectral signature of the AOD (expressed via Angström exponent) as a first order indicator of the aerosol particle size. These are now considered the “basics” for any aerosol mission.

Vertical profile of parameters is only achieved by active techniques that also have the advantage of day-night observation. But the lack of swath is very limiting for monitoring applications.

The A-train constellation of satellites with active (Caliop/Calipso) and passive sensors

(MODIS/Aqua, OMI, POLDER/Parasol) provides the most advanced aerosol products suite so far, namely fine mode fraction, spherical/non-spherical fractions, effective radius, single scattering albedo, layer altitude.

2.2 Comparison of performances

Beyond the qualitative survey above a more quantitative comparison of aerosol parameter accuracies reveals a broad range of performances in terms of aerosol parameters, even for the fundamental ones.

Especially two recent papers highlight large differences among products. The one by Kokhanovsky et al (2010), compares aerosol retrieval algorithms over land for a single scene over Europe, whereas Bréon et al (2011) compare 5 sensors products against Aeronet over as long as 5 years of data, both over ocean and over land.

The following figures [Fig.3 to 6], reported from Bréon et al (2011), show density histograms of the spaceborne estimates of the AOD @ 670 nm against AERONET sunphometer measurements.

The dashed lines (0.03 + 0.08*τ over ocean, 0.05 + 0.15*τ over land) are indicators for the highest quality retrievals used for computing the Good fraction Gfrac.

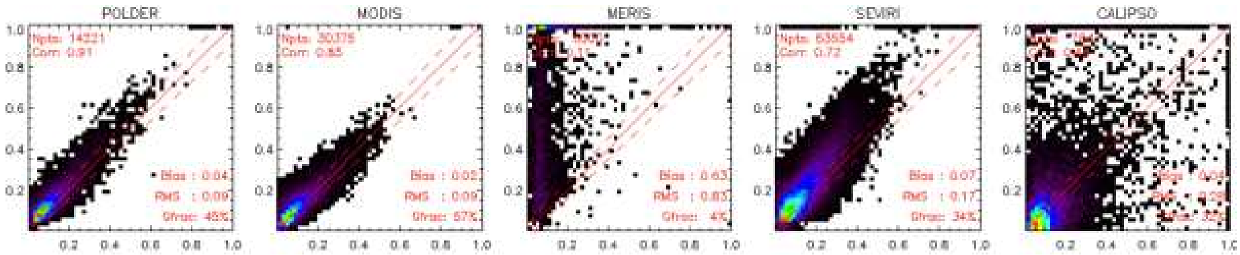


Figure 3 : Total Optical Depth, Oceanic cases (from Bréon et al., 2011)

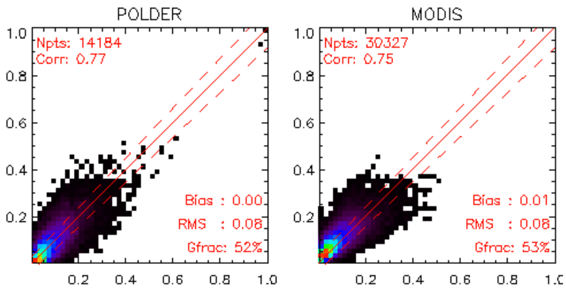


Figure 4: Fine mode Optical Depth, Oceanic cases (from Bréon et al., 2011)

Over Ocean 'operational' MERIS and day Calipso product performances are insufficient (correlation coefficient from 0.12 to 0.27 at most) even after selecting of the best quality flags. SEVIRI performance is intermediate (correlation of 0.73 to 0.77) but has a decisive advantage in terms of temporal coverage that make the product unique for use in the models.

Higher quality AOD are provided by MODIS and POLDER (correlation coefficient from 0.83 to 0.85 for MODIS and from 0.88 to 0.91 for POLDER).

Current ocean AOD accuracies are estimated for MODIS at $\pm 0.03 \pm 0.05\ \tau$ (Remer 2002, 2005) and for POLDER/PARASOL at $\pm 0.05 \pm 0.05\ \tau$ (Tanré et al, 2011).

Over land, the same comparison exercise shows even more scattered results, especially for MERIS and SEVIRI.

Only MODIS promises AOD over low reflective land surfaces with reasonable (correlation of 0.86, rms of 0.11) accuracy: 0.05 + 0.15 τ (Chu, 2002; Remer, 2005)

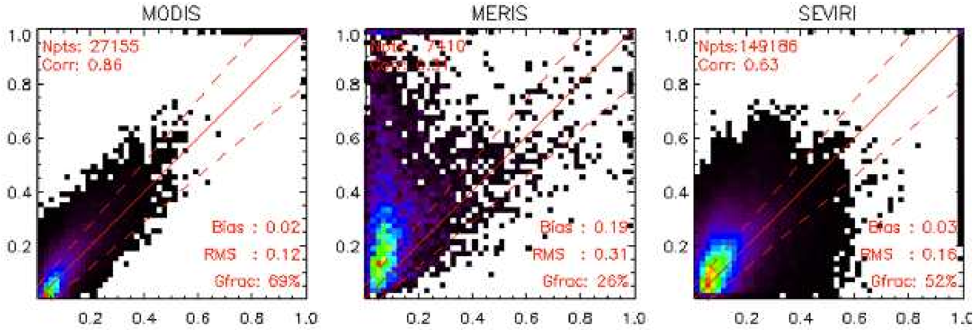


Figure 5: Total Optical Depth, Land cases (from Bréon et al, 2011)

Fine mode AOD fractions over land are only provided by POLDER with RMS errors of 0.11 and MODIS with an RMS error of 0.14. The polarization technique gives the best results for the small polarizing particles i.e. for biomass burning and pollution aerosols which are key elements for air quality monitoring.

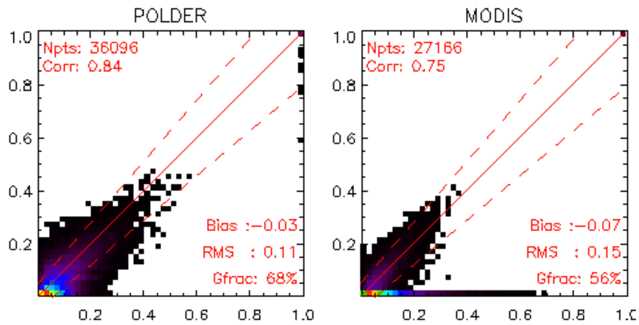


Figure 6: Fine mode Optical Depth, Land cases (from Bréon et al., 2011)

Similar conclusions arise from other current intercomparisons performed in the frame of projects such as AEROCOM or CCI/CERA which include also ATSR products (work in progress).

More advanced parameters such as effective radius, non spherical fraction, asymmetry parameters indicative of aerosol size and shape are restricted to open oceans and still only available at research level.

A key parameter for climate studies is the aerosol absorption. Although several attempts have been made and the OMI instrument retrieves some information about absorption, the retrieval of aerosol single scattering albedo and its spectral variation from space remains the primary insufficiency.

The conclusion is that, despite very significant progress in the last two decades, retrieval of aerosol parameters from space observations is still far from the level of performance of ground based measurements and is not at the level of user requirements. Especially the performance is poorer over land than over ocean, whereas the user request would be at least similar.

A significant effort has to be made in order to achieve a similar level of performance between land and ocean.

2.3 Looking for continuity

Regarding climate applications continuity of observations is a critical issue.

As seen on Table 1 the longest records (AVHRR since 1981 and TOMS since 1979) are presently limited to AOD over ocean (from AHHRR) and a qualitative aerosol index over land (from TOMS).

The most advanced parameters come from the A-train constellation which is by nature a research partnership based on sharing opportunities and consequently has *not* been designed for continuity.

Most sensors on the A-train have already exceeded their design lives.

Despite the great success of the A-train constellation no plan for follow-on missions addressing aerosol observations exists so far [see Fig. 7].

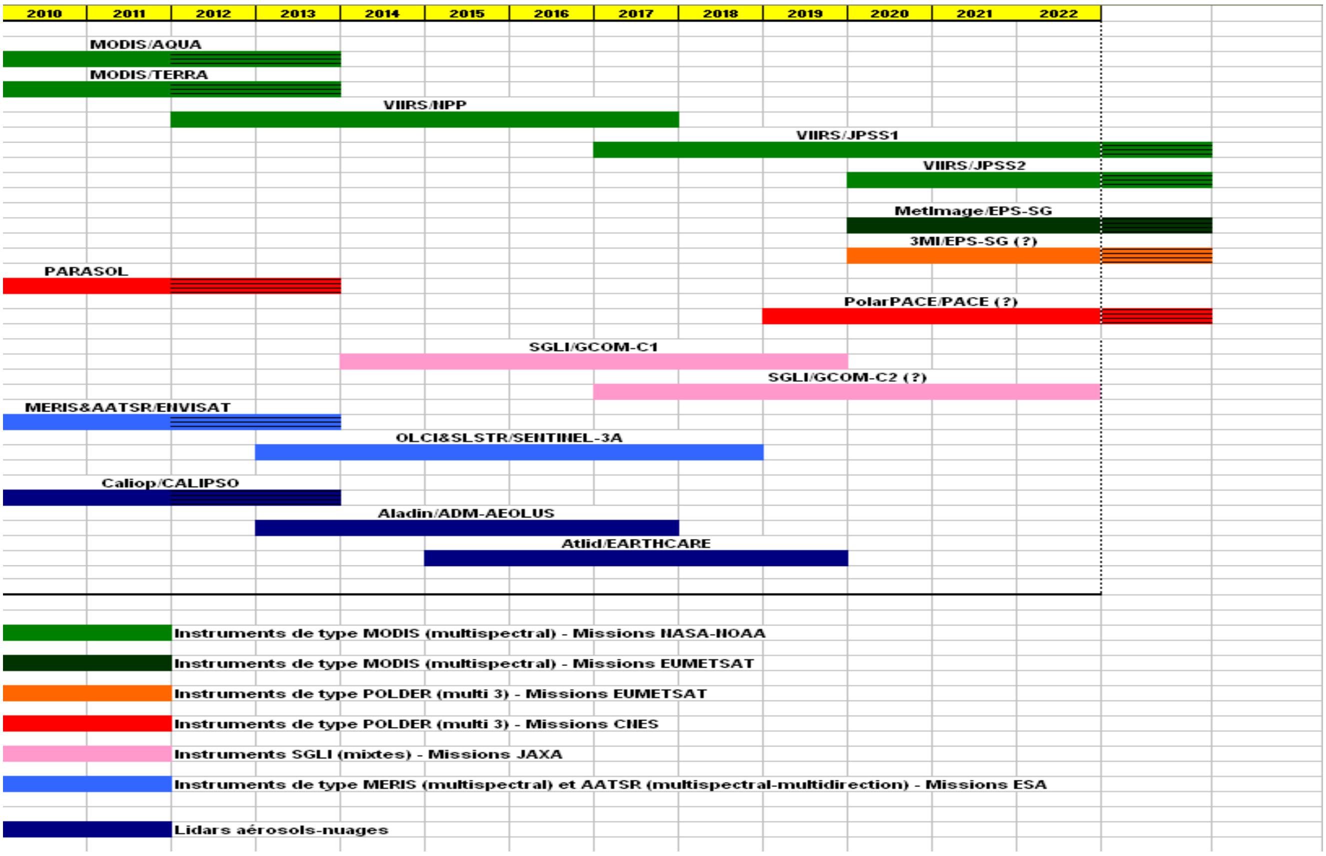


Figure.7: timeline of future missions [Credits D.Renaut]

Even if Glory 2 re-flight can be achieved by NASA, the APS instrument swath of 7 km is by far insufficient to answer the need for global coverage. NPP will fly (2011) with VIIRS, a MODIS like instrument at an altitude of 825 km. JPSS with VIIRS and OMPS (successor of TOMS) has been delayed after 2016.

On the ESA side there is no dedicated aerosol instrument as such. The ATSR series was primarily designed for SST whereas MERIS was for ocean colour. MERIS aerosol products are by-products of the atmospheric correction over ocean and tentative over land. Initial efforts to change this in the framework of the GlobAEROSOL ESA DUE project were not too successful. Even though a 12 year ATSR climatology for AOD and Angström were eventually prepared the quality of the aerosol products was well below that provided by MODIS, MISR or POLDER. In addition, the merging of different sensor products (ATSR, MERIS and SEVIRI) was not really satisfactory. This may change in forthcoming years with the ESA CCI initiative that develops new aerosol algorithms for ATSR, MERIS and Sciamachy in terms of aerosol load. Still the data constraints by those sensors are weaker than those offered by muti-spectral, multi-viewing and polarization capabilities such as POLDER and 3MI.

The GMES enterprise has recognized continuity as a key driver for applications and will ensure the follow-on of present ENVISAT sensors. Sentinel 3 will carry the OLCI and SLSTR instruments which will take over MERIS and AATSR with more spectral bands to cover he full MODIS range.

On the EUMETSAT/NOAA operational programmes cloud imagers designed for meteorological purposes become more and more advanced and future generation deserves growing attention for aerosol. LEO imagers (VIIRS, MetImage) will provide follow-on to MODIS (Terra 10:30 & Aqua 13:30) sensors with different equator crossing time (9:30). Regarding GEO observations, as seen before, SEVIRI on MSG provides already valuable aerosol information. FCI on MTG is very promising.

On the Japan side GCOM-C1 will fly SGLI, a full spectral imager with an endeavour toward the 3M space: 1 channel in the UV, 2 directions (one for the total radiance, one for the polarization) and 2 polarized channels.

2.4 Categorization of sensors in terms of observation capabilities

To better understand the difference among various sensors performances we now look at the sensors observation characteristics reported on the following table.

Instrument	Spectral channels for aerosols (nm)	Viewing geometry	Polarization (Q,U)	Swath (km) Resolution (km) Frequency/day Geo
AVHRR AVHRR-3	1λ (VIS) 670 3λ (VIS, SWIR-) 630,863,1610	1 obs angle	No	2800 km 1 km
TOMS OMI	3λ (UV) UV-1, 270-314 nm, UV-2 306-380 nm VIS 350 – 500 nm	1 obs angle	No	2600 km (114°) 15 km
ATSR-2 AATSR	4λ (VIS, SWIR) 555,659,8655,1610	2 obs angles [0°-22°, 55°]	No	500 km 1 km
MERIS	13λ (VIS) 412,443,490,510,560,620,665,681,709,754,779,865,885	1 obs angle	No	1150 km 1 km
POLDER 1-2 POLDER 3	5λ(VIS) 443,490,565,670,865 Id + 1020	12 to 14 obs angles [-55° to 55°] 16 obs angles	Yes 443, 670,865 490, 670,865	2400 km 7 km 1700 km 6km
MODIS	15λ (VIS, SWIR)	1 obs angle	No	2330 km

	412,443,490,510,560,620,665,681,709,865,885,1240,1370,1640,2130 + 2λ IRT			250 m to 1km
MISR	4λ (VIS) 446,558,672,866	9 obs angles [0°, ±26°,±46°,±60°,±70.5°]	No	360 km 250m
SEVIRI/ MSG	4λ (VIS, SWIR) HRV,VIS0.6, VIS08, SWIR + 3λ IRT	57 obs angles/day 1 every 15 minutes	No	GEO Disk 3 km
VIIRS	*15λ (VIS, SWIR)* 412,445,488,555,620,640,672,746,855,865,1240,1378,1610 ,2250,3740 + 3λ IRT	*1 obs angle*	*No*	*3000 km* *750 m*
APS	*9λ (VIS, SWIR)* *412,443,555,670,865,910,1378,1590,2250*	*180 obs angles* *Range [-55°,55°]*	*Yes* *9 bands*	*7 km* *7 km*
SGLI	*12λ (UV, VIS, SWIR)* *380,412,443,490,530,555,673,868 1050,1380,1630,2210* + 2λ IRT	*2 angles* ±46°		*1150 km* *250-500m*
MetImage	*16λ (UV, VIS, SWIR)* *354,388,405,443,470,490,555,670,708,763,865,1020,1240,1365,1630,2250*	*1 obs angle*	*No*	*106-110°* *500m*
FCI/MTG	*8λ (VIS, SWIR)* *HRV,VIS0.6, VIS08, SWIR 1.3,1.6,2.2 + 5λ IRT*	*>80 obs angles/day* *1 every 10 minutes*	*No*	*GEO Disk* *10 minutes* *1 to 2(IRT) km*
3MI	*13λ (UV, VIS, SWIR)* *354,388,443,490,555,670,763,765,855,910,1037,1650,2130*	*10 to 14 obs. angles*	*Yes* *8 bands*	*2400 km* *4(VIS) to 8(UV) km*

Table 2 : Spectral, Directional & Polarization capabilities of passive aerosol sensors [adapted from Kokhanovsky]. Swath, spatial resolution (native at nadir) and coverage are also reported.

All sensors have multispectral capabilities, with a minimum of 2 bands, up to a full suite of bands, including absorbing and non absorbing bands for selected purposes (O_2, H_20, O_3).

Even more important than the absolute number of bands one shall pay attention to the available spectral domain and distinguish between VIS-NIR, SWIR and IR capabilities.

All sensors have VIS-NIR channels, fewer have additional SWIR or UV, only APS and SGLI would have full SWIR +UV.

For directional capabilities, the range is minimal for ATSR, SGLI (2 views), intermediate (9 to 14-16 for MISR and POLDER) and maximal (57-180) for APS and SEVIRI. Note however that GEOs sensors don't have near instantaneous multi-angle capabilities.

Finally the polarization capability is provided only by POLDER so far and planned for APS and SGLI (although limited for the latter).

We now propose to summarize the sensor capabilities along 6 axes: spectral, directional, polarization, coverage, resolution and temporal with rating according to the following rule:

0 for nul, + for minimal, ++ for intermediate , +++ for high, ++++ for maximal.

The two attributes coverage and revisit are used to differentiate LEO from GEO.

The coverage refers to swath width for LEO sensors and limitation to a disk and lower latitudes for GEO.

The temporal revisit results from the swath width for LEO and observation frequency for GEO sensors.

The sensor Table 2 then simplifies into the following Table 3

Capabilities Instrument	**Spectral channels for aerosols**	**Directional**	**Polarization**	**Coverage**	**Spatial Resolution**	**Temporal (Revisit)**
AVHRR	+	0	0	++++	+++	+++
TOMS/OMI	+	0	0	++++	+	+++
(A)ATSR	++	+	0	+	+++	+
MERIS	+	0	0	++	+++	++
POLDER	+	+++	++	+++	+	+++
MODIS	+++	0	0	++++	+++	+++
MISR	+	++	0	+	++++	+
SEVIRI/MSG	++	+++	0	++	++	++++
VIIRS/NPP	+++	0	0	++++	+++	+++
APS	+++	++++	++++	0	+	+
SGLI	++++	+	+	++++	++++	+++
MetImage	++++	0	0	++++	++++	+++
FCI/MTG	+++	+++	0	++	+++	++++
3MI	++++	+++	+++	++++	++	+++

which can be viewed more easily when represented in radar plot fashion. The following figure 8 shows the evolution of sensor capabilities along time on 4 panels: legacy, current, and future sensors; GEO sensors are on a separate panel.

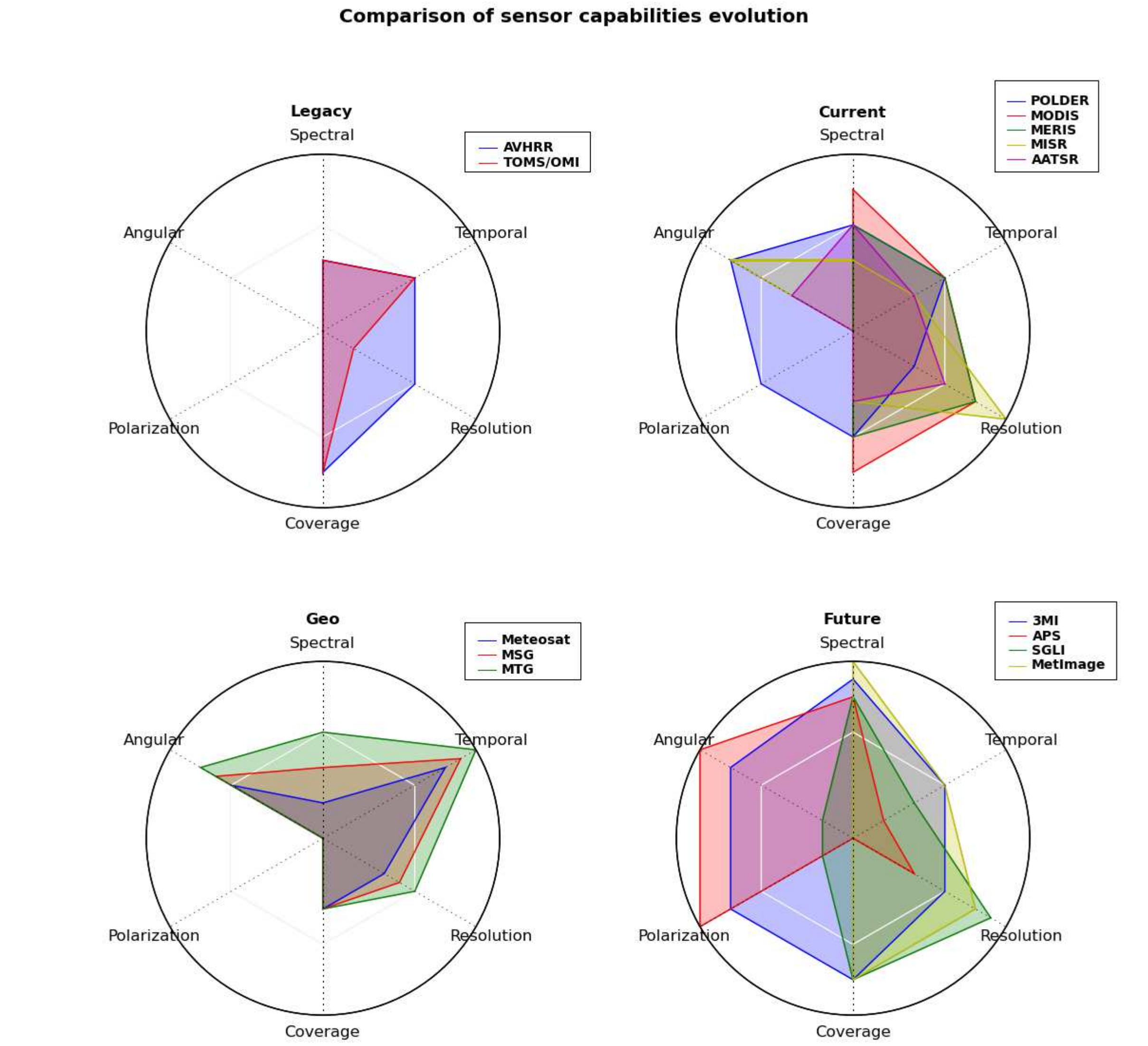


Figure 8: illustration of past, present and future ***sensors capabilities*** *along spectral, directional, polarization, coverage, resolution and temporal dimensions [Credits J.Riedi]*

The figure clearly highlights:

- a significant increase of sensors capabilities with time along all directions.

- the unique superiority of GEO sensors regarding temporal performance. Combining LEO with GEO observations is the only (but powerful when available) mean to fully cover the temporal space

- the good coverage by "MODIS-class" and future meteorological imagers of the right half disk corresponding to spectral, coverage and resolution space …but the lack of abilities in the left-hand space where critical information on aerosol is missed (as explained in §2.5)

- the well balanced skills but also present limitations of the POLDER concept when compared to other instruments

- the advances expected from the 3MI design (detailed in §5).

2.5 Linking observation capabilities to aerosol performance

2.5.1 Basic physical process

The signal measured at the top of the atmosphere (for passive and clear sky observations) results from scattering in the atmosphere and interactions with the surface, with attenuation by absorption. Any aerosol inversion scheme task is to unravel the aerosol signal from the surface contribution and to interpret this signal in terms of aerosol optical properties (amount, size and absorption). Scattering (including reduced scattering by absorption) in the solar spectrum is very sensitive to wavelength, geometry of observation and polarization. This explains why spectral, directional and polarization are 3 " keys" to aerosol retrieval.

2.5.2 Spectral information

Absorption can be addressed separately by using **absorbing channels**, especially in the **UV** domain where O_3 is also absorbing. Unfortunately in this range not only the absorption but also the altitude of the scattering comes into play and adds some ambiguity to the retrieval. This is why for example TOMS/OMI are very efficient with detecting absorbing aerosol even over desert areas and over cloudy scenes but with performances limited to an absorbing aerosol index.

Back to scattering properties, the **spectral information** is used primarily for this purpose and all sensors have a minimum set of bands in the visible domain **(VIS)** [see table 2].

The problem is easier to solve ***over ocean*** because, except in coastal areas, the water is almost black in the NIR part of the VIS spectrum. ***Over land*** the surface contribution may be large and variable. When the surface is bright the sensitivity to the presence of aerosol decreases and the retrieval is more complex according to aerosol absorption. Moreover external factors such as cloud screening and uniformity are also more difficult issues over land. Assumptions and/or extra information are necessary to solve the problem.

Additional spectral information in the **SWIR** (at 2.1-2.2µm) is powerful when available, especially over dark vegetation. For example the MODIS algorithm uses an empirical relationship between the visible and near-infrared (1.6 and 2.1 µm, where the aerosol signal is much smaller) reflectances to prescribe the surface albedo in visible retrievals. The empirical relationship is only valid over vegetated surfaces (dark targets) so that no retrieval is possible over desert areas.

This is why sensors like MERIS with capabilities limited to spectral information in the visible (VIS) have very limited skills over land. The SLSTR instrument on Sentinel 3 will have the adequate SWIR channels and may be used to supplement OLCI over land.

Going to longer wavelengths SWIR (or even IRT as with SEVIRI) also brings more sensitivity to larger aerosols like dust or ash particles whereas shorter wavelengths are more suited for finer pollution particles.

The more spectral channels the more insight can be obtained on the aerosol physical properties such as the size distribution or refractive index.

MODIS has demonstrated that along with spectral AOD fine mode fraction (ocean & land), effective radius and asymmetry factor (ocean only) can be achieved, although the information is more qualitative than quantitative in nature.

In summary, the spectral skill gives access to total optical depth and aerosol size information.

- VIS/NIR is mandatory and sufficient for AOD basic retrieval over ocean or dark surfaces,
- UV is necessary (but not sufficient) for retrieving absorption information,
- SWIR is mandatory for retrieving AOD over land and suited for the coarser particle mode.

2.5.3 Directional Information

Rather than increasing the number of spectral channels to augment the information content, an alternative approach is the use of multi-directional information for the same scene (e.g. MISR, ATSR) or over time with the assumptions that aerosol does not change with time (e.g. Meteosat, GOES, SEVIRI) or that the surface properties do not change with time (e.g. for a 16-day cycle in an exploratory MODIS algorithm) to constrain unknown elements in aerosol retrievals.

Another straightforward advantage of directional sensors is that glint conditions can be avoided for aerosol retrievals.

2.5.4 Polarization Information

As illustrated on the inset [Fig. 9] polarization is mostly driven by scattering properties which by themselves are very sensitive to the geometry of observations and to the shape of scatterers. This explains why polarization, when associated with directional capabilities has unique advantages for aerosol and clouds retrievals.

Discrimination between spherical and non spherical particles becomes possible and is a powerful means for differentiating sea salt form dust particles over ocean as well as identifying ice clouds from water clouds in the cloud screening process. Cloud droplet size can also be estimated based on the multi-directional signature of the polarized reflectance.

Relatively easy retrieval of small polarizing aerosol particles from pollution or biomass burning is also possible even over land where conventional spectral technique require much more channels and still have more difficulties.

Last but not least detection and retrieval of aerosol over overcast liquid clouds can be achieved.

This is the basic concept for the POLDER missions whose results (presented in §3 herafter) fully demonstrate the benefice of using polarization.

A few very recent papers also support the high value of polarization measurements not only for allowing more aerosol parameters but also for improving the performance of aerosol retrievals. By adding more constraints, especially on the aerosol (directional) phase function, discrimination of the aerosol model can be achieved leading to less ambiguity and more precise estimation of the aerosol parameters.

Khokanovsky et al (2011) compared current aerosol retrieval algorithm and concluded that "multi-angular spectropolarimetric measurements provide more powerful constraints compared to spectral intensity measurements alone".

Hasekamp et al (2011) developed a new retrieval algorithm suited to Parasol observations over ocean. In addition to AOD and Angström coefficient, they are able to retrieve refractive index, single scattering albedo with very good accuracy compared to Aeronet. They estimated the Degrees Of Freedom for Signal (DOFS) of Parasol observations to range between 5 and 12, depending of the geometry of observations. This is much higher than for intensity measurement only.

These results confirm the promising results from Dubovik et al (2011) retrieving at once the complete set of aerosol parameters and underlying surface by applying statistically optimized inversion algorithms to the large number (over one hundred per pixel) of 3M observations.

The great sensitivity of polarization to particle shape also applies to cloud particles, especially cirrus. Simultaneous retrieval of aerosol and cloud properties is also in the scope an gives already very promising results with Parasol (see §4.3.3 , Waquet, 2011, in preparation)

Finally, by measuring the masking effect of enhanced Rayleigh scattering in the UV polarization should be a clever solution to the altitude ambiguity which presently limits the spectral absorption technique in this range (cf TOMS, OMI limitation). At least one polarized channel in the UV domain (360 to 380 nm) would be required.

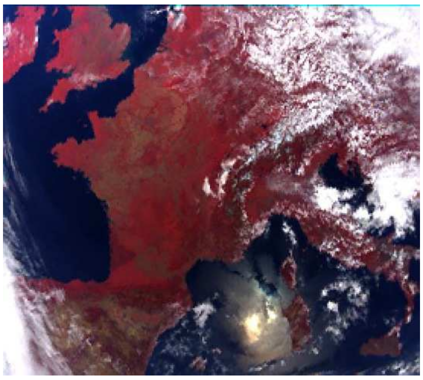
2.5.5 In summary

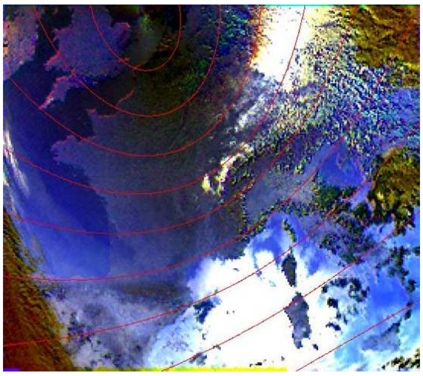
The combination of **Multi-spectral with Multi-directional and Multi-polarization** information expands the dimensional space of the passive observations and opens the way to a more advanced generation of algorithms able to retrieve a full set a aerosol parameters with much improved accuracy and together with the surface boundary conditions. This is what we call the “3M” capability.

“Why polarization with 3M is the trick ?”

The striking differences between couples of images of the same scene observed in natural and polarized light reveals the potential of polarized observations.

Fig. 9: Couple of POLDER-1 first images





Natural light *Polarized light with scattering angle isolines*

On the polarized image the geographic contours can hardly be recognized. This is because polarization from molecular scattering in the atmosphere prevails over the polarization contribution from the surface. This explains why the colour blue is predominant on polarized images taken in clear sky conditions and why there is little contrast between land and sea.

Once molecular scattering and ground polarized contributions have been substracted, the residual signal provides information on aerosol load in the atmosphere.

The surface of the ocean acts as a mirror which generates highly polarized light leading to a bright spot on both images corresponding to the glitter pattern whose intensity decreases with the surface roughness (wave slope).

Apart from reflection phenomena, the polarized component measured at the top of the atmosphere results primarily from single scattering by the atmosphere molecule and aerosol, which depends strongly on the scattering angle. Polarized images are thus easier to interpret by overlying scattering angles isolines.

Last but not least single scattering phase functions are highly sensitive to particle shape and reveals inmost details of micronic scatterers such as sphericity/non sphericity of salt/dust particles, droplets in the rainbow or oriented ice crystals in clouds!

3 POLDER as a proof of the 3M concept

3.1 POLDER/PARASOL story

The first and still the only “3M” observations available to date are from the POLDER series of instruments. The POLDER instrument was developed by CNES through a cooperation with NASDA and was launched in August 1996 on ADEOS-I . Following a platform failure after 8 months of operation a second instrument was furbished for ADEOS-II launched in December 2002. Again, the platform failed after 7 months. A third instrument was then developed to fly on a dedicated CNES microsatellite that was launched in December 2004 and joined the A-train in March 2005. After more than 6 years of operations PARASOL mission has been extended to 2013, but drifts now away from the A-train.

POLDER level 1 processing and data distribution is performed routinely by CNES.

The scientific processing has been shared between CNES and French research laboratories.

Since 2003 the ICARE data & services centre has taken over the processing and distribution of POLDER/PARASOL atmospheric products. POLDER archive data are processed consistently with PARASOL data.

Altogether, despite two unfortunate interruptions, more than 15 years of experience have been acquired continuously by the POLDER/PARASOL teams on calibration, image quality, and algorithms for processing 3M observations. Since the A-train meetings (Lille 2007 and New Orleans 2010) continuously growing interest is developing in the user international community for this unique set of observations.

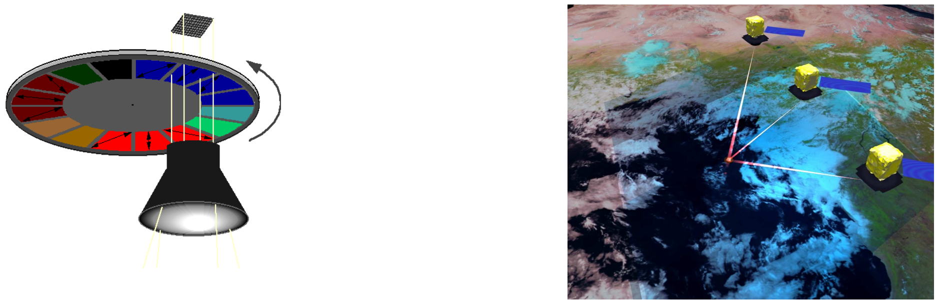
The whole set of POLDER products is available to users on ICARE website along with other instruments products and interactive tools for synergistic use.

POLDER dataset		
POLDER 1/10/1996 – 30 /06/1997	POLDER2 14/12/2002–25/10/2003	PARASOL 4 Mar 2005-…

3.2 POLDER as a simple ‘3M’ instrument

POLDER instrument is most simple [Fig 10]: a CCD camera (274 x 242 pixels) with a very wide field of view (FOV ± 50°) and a rotating filter wheel in front carrying 15 filters and polarizers [Fig.10-left]. The camera takes a set of pictures every wheel turn (20 seconds).

Figure 10 : POLDER instrument concept



The key point lies in the **2D FOV** which provides both a very large swath across track (2200 km for POLDER, 1400 km for Parasol) and the multidirectional capability along track. Indeed, when combined with the satellite motion (6 km/s), repeated observations (up to 14 to 16) of the same target are acquired with varying viewing angles [Fig 10-right]. Moreover from one day to the next the satellite ground track shifts providing additional views to complete the sampling of the surface BRDFs.

This basic concept allows for a compact (80x50x25 cm^3 for POLDER1&2 and 50x50x30 cm^3 for Parasol) and very light instrument (30 kg) compared to the other instruments listed above which, except APS (58 kg), are in the 150-230 kg range.

Another specificity of the POLDER approach has been to entirely rely on in flight vicarious calibration and extensive on ground characterization of the instrument to achieve the geometric and radiometric accuracy requirements. This choice has proven to be successful in terms of performances (Hagolle et al, 1999; Fougnie et al, 2007) and is also a reason for POLDER light weight.

NB One shall keep in mind that the level 1 processing of a 3M instrument deserves an important effort both for geometry (registration of the different channels and views) and radiometry (3x components of the field vector).

Simple by design, robust and reliable by experience are major assets of the POLDER instrument concept.

3.3 POLDER results

Over the course of three missions (§3.1), POLDER has provided a unique dataset to study and better understand aerosol and cloud radiative effects and microphysical properties. Especially, the highly successful PARASOL mission, spanning more than 6 years of continuous data, has led to an unprecedented view of the aerosols and clouds properties at global scale.
Animations of aerosol parameters can be viewed on the ICARE gallery .

3.3.1 Polarization for aerosols over ocean

Although not critical for optical thickness retrievals, the polarized and directional measurements provide a powerful constraint on aerosol models (Deuzé et al, 1999 and 2000; Herman et al, 2005), not to mention the clear advantage of multi-angle measurements to prevent the sun glint "blind zone".

Over ocean, these allow to separate the fine aerosol component due to anthropogenic activities from the coarse mode resulting from natural processes. Moreover, when the scattering angle range sampled is large enough (90°–160°), POLDER can discriminate large spherical marine aerosols from non-spherical desert aerosols, retrieve the effective radius of the accumulation and coarse modes and evaluate the real part of the refractive index. These optical quantities are critical information to distinguish between biomass burning, pollution, dust, sea-salt aerosol types (Fig. 11).

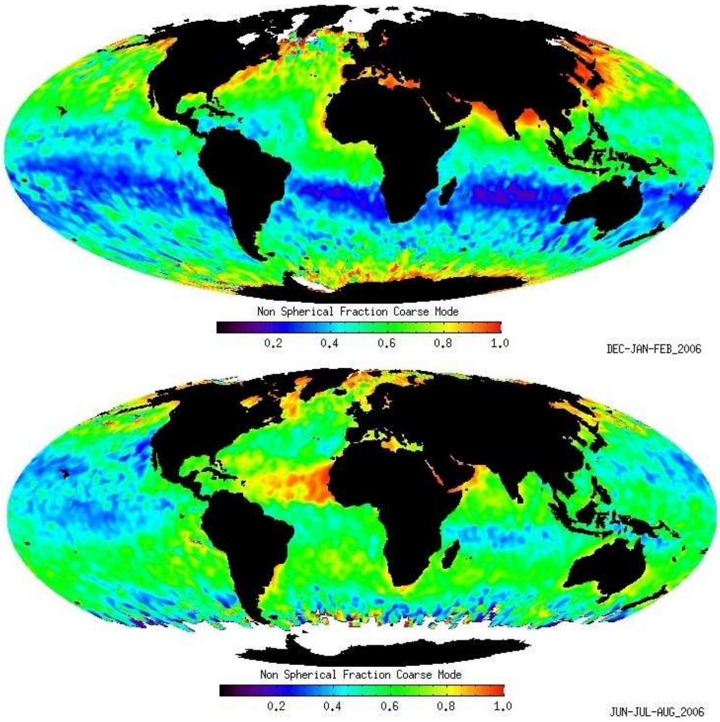


Figure 11: Contrast between winter and summer seasons for the ***non spherical fraction of the aerosol coarse mode*** *derived over ocean from the Parasol polarization measurements*

Furthermore, polarization measurements at POLDER shorter wavelength (490 nm) carry information on aerosol layers height. Ambiguity currently remains due to under constrained single scattering albedo values but future generation of algorithm (see §4.4) and even shorter wavelengths available on 3MI are expected to improve significantly accuracy of those retrievals (Waquet et al, 2009).

3.3.2 Polarization for aerosols over land

Over land surfaces that are highly reflective, POLDER uses the polarized radiance to reduce the surface contribution (Deuzé et al, 2001). Again, since polarization is mainly sensitive to the presence of small particles, it allows to derive the optical depth of the fine mode only. The location, the strengths and the seasonal variability of the aerosol sources can be then assessed at a global scale as shown on the 5 years panel [Fig.12].

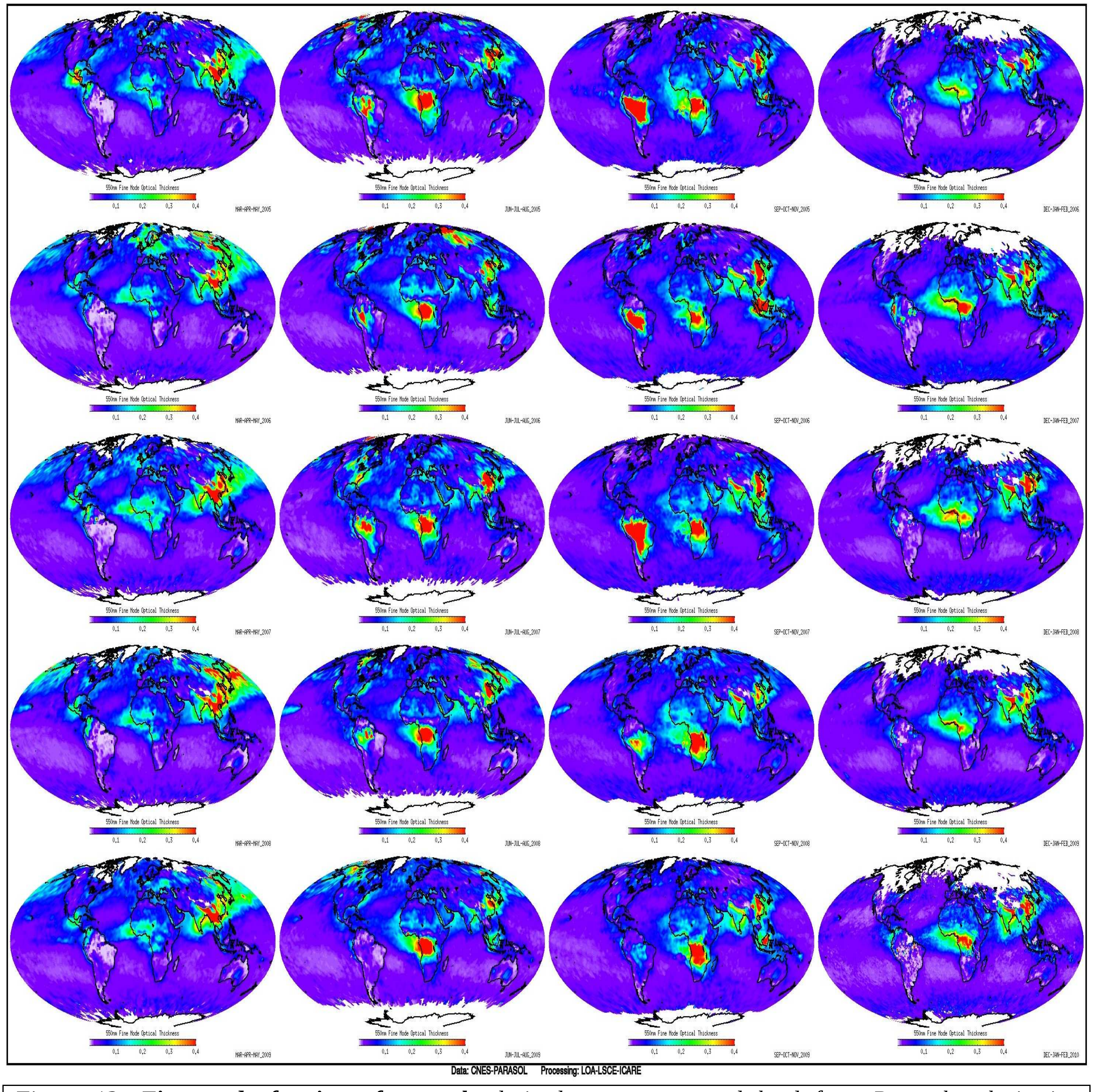


Figure 12: ***Fine mode fraction of aerosols*** *derived over ocean and land from Parasol polarization observations. Sources and transport of pollution and biomass burning aerosols can be monitored at global scale. [Credits ICARE]*

An extensive validation of POLDER products over land has been carried out against AERONET measurements which demonstrates the robustness and quality of the information retrieved over land [Fig. 13] (Goloub et al, 1999 ; Fan et al, 2008 ; Breon et al , 2010).

X. Fan et al. / Remote Sensing of Environment 112 (2008) 697–707

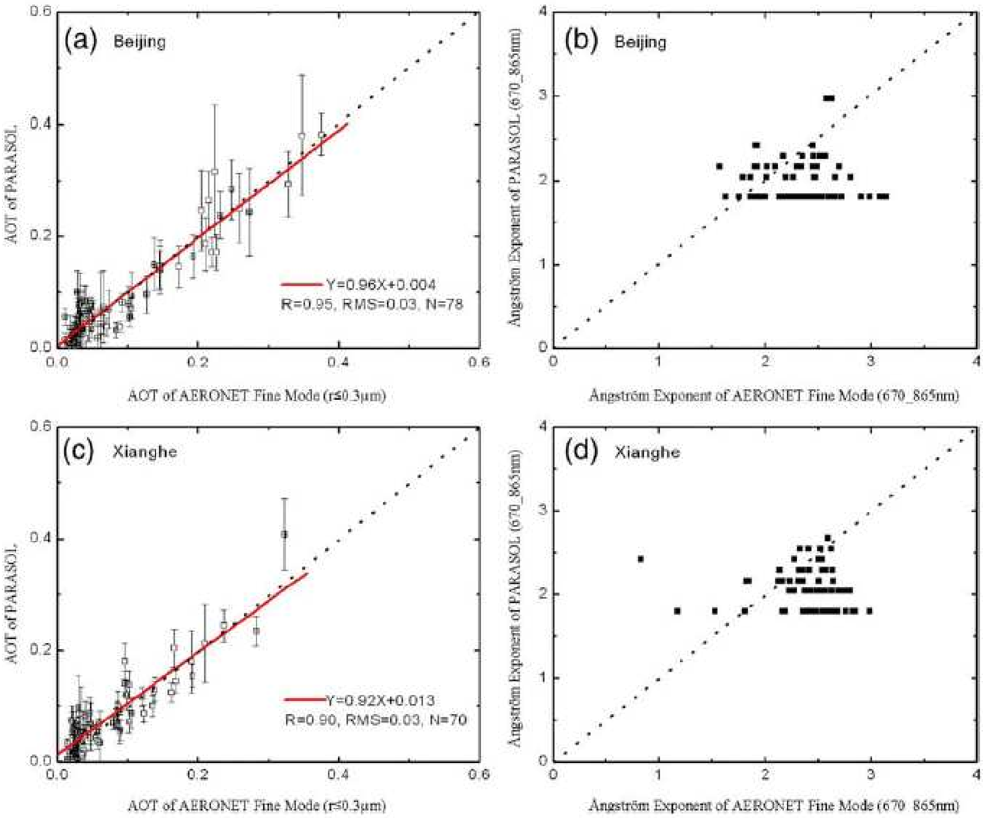


Fig. 8. PARASOL AOT and Ångström exponent versus those of AERONET fine mode for Beijing (a, b) and for Xianghe (c, d).

Figure 13: Validation of ***Parasol fine mode and Angström exponent*** *against sunphotometers over China for the period March 2005 to May2006) [from Fan et al, 2008]*

POLDER fine mode optical thickness accounts for particle size up to 0.4 µm, which corresponds to the range of particles important regarding health.

Initial studies (CNES/INERIS study; Kacenelenbogen et al, 2006) indicate that POLDER fine mode products provide a meaningful source of information for Air Quality assessment and monitoring, as illustrated on figures 14 and 15.

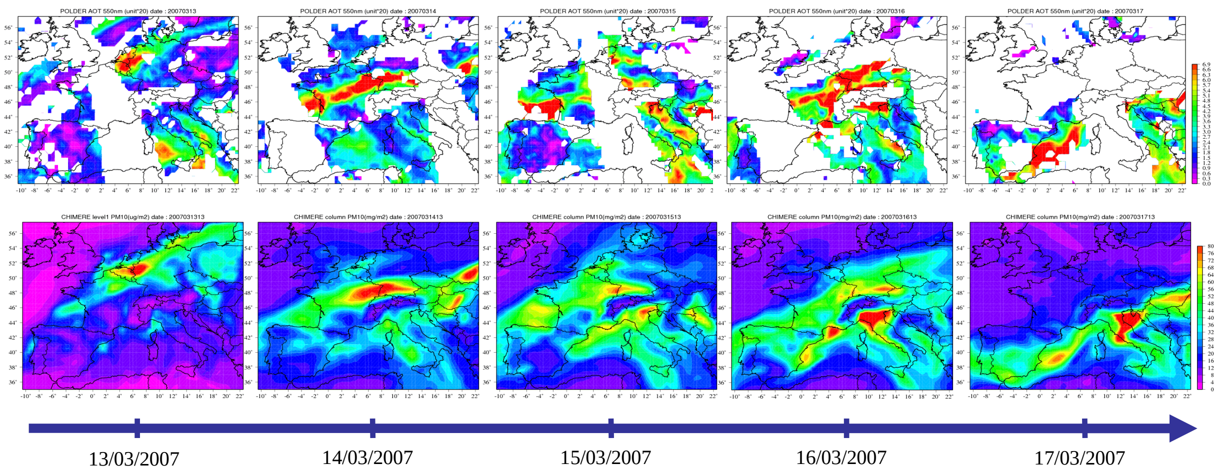


Figure 14: Comparison of POLDER fine mode optical thickness and CHIMERE column of aerosol (PM10) during a pollution episode over Europe in 2007 [Credits INERIS]

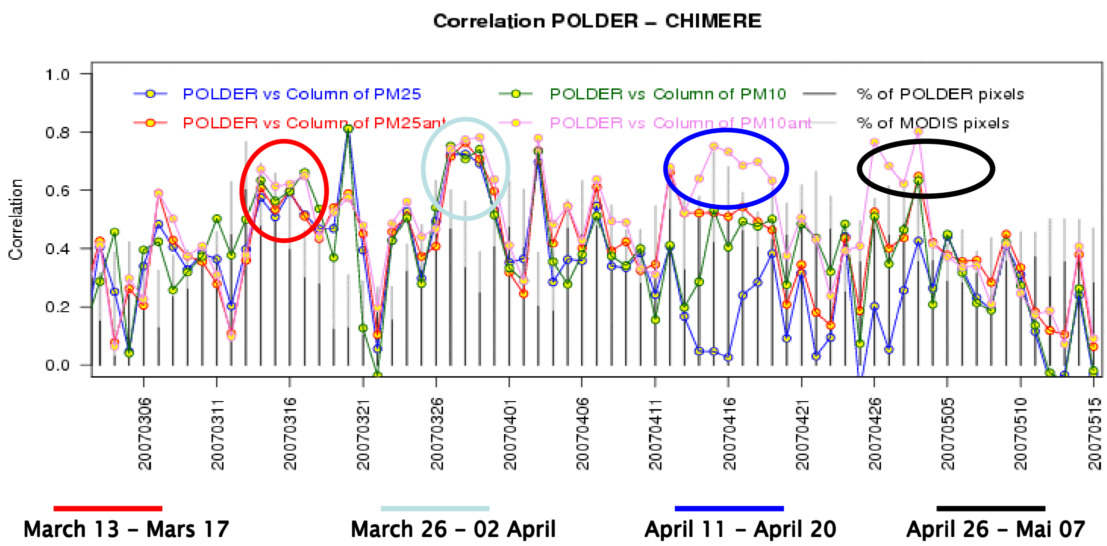


Figure 15: Daily correlation between POLDER aerosol optical thickness (AOT) at 550 nm and column of aerosol (PM2.5, PM10, and their respective anthropogenic fraction) from CHIMERE chemistry transport model [Credits INERIS]

On a more prospective level, preliminary studies over land have shown the potential of polarization to derive aerosol layer altitude but practical implementation with PARASOL is limited by cloud contamination and lack of polarization measurements at 443 nm which were previously available on POLDER 1 and 2 (Tanré et al, 2011).

Finally, the latest methodological developments by Dubovik et al (2011) currently allow for the simultaneous retrieval of both aerosols and surface properties based on a completely coherent constraint of all POLDER observations. This new generation algorithm can be used to retrieve aerosol normalized size distribution and concentration as well as the non spherical fraction and spectral variation of the refractive index (real and imaginary) from which can be computed all other relevant optical and microphysical properties of aerosols. As shown in Fig. 16, this enhanced retrieval technique can provide highly accurate and detailed aerosols properties over land, including over bright surfaces.

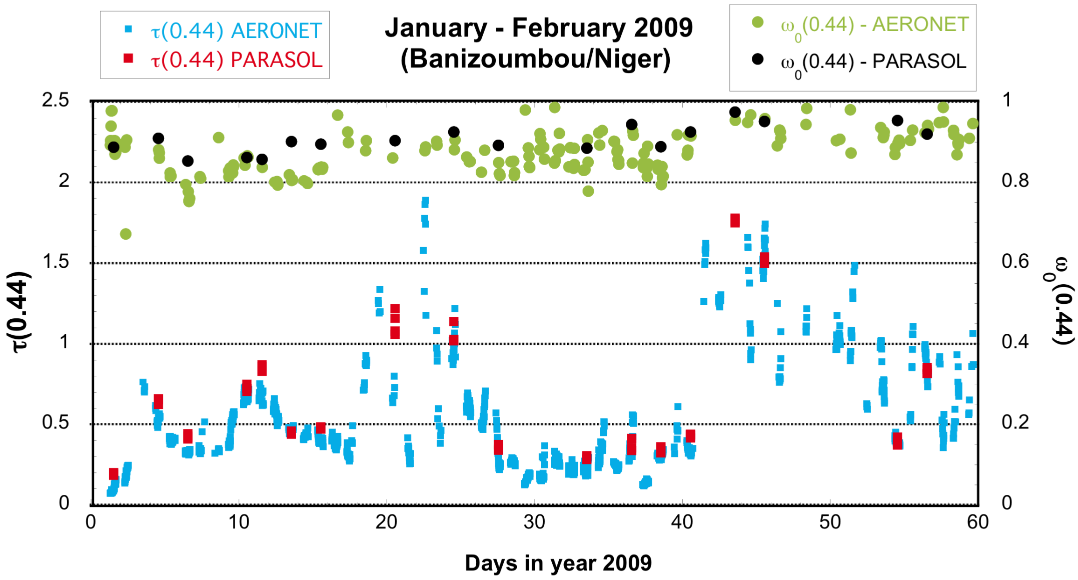


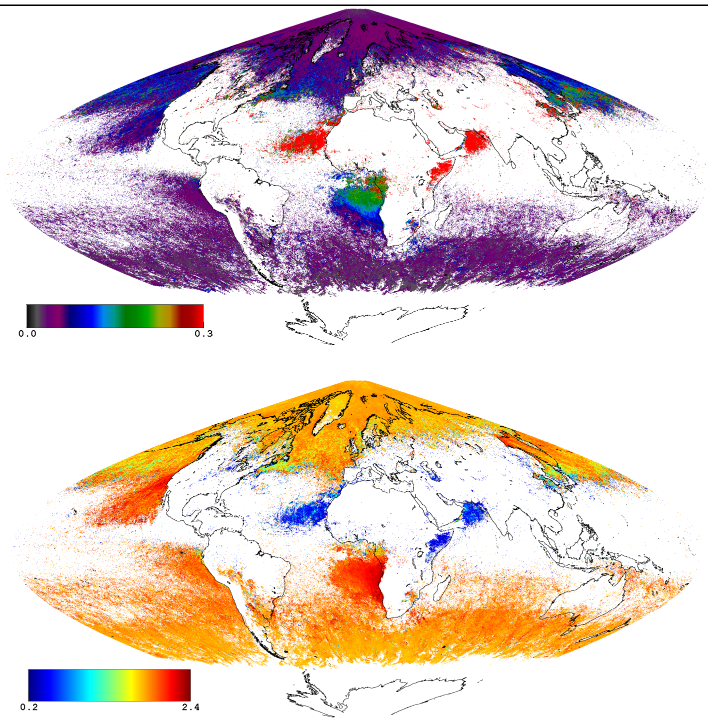
Figure 16: Example retrievals of optical thickness and single scattering albedo from PARASOL using the algorithm developed by Dubovik et al (2011) compared to AERONET for 2 months over Banizoumbou/Niger (bright surfaces). [Credits O. Dubovik]

3.3.3 Polarization for aerosols over clouds

Quite surprisingly, the polarization and multiangle measurements have recently proved invaluable for deriving aerosol information above cloudy areas which are almost always discarded from aerosol retrievals.

Combining data from the POLDER and MODIS sensors, Waquet et al (2009) have developed an operational algorithm which allows to retrieve aerosol properties above clouds and provides unique information for computation of aerosol radiative forcing above clouds (Fig. 17).

The technique developed also enables to better constrain aerosol absorption properties because of the transmittance-like signal that is being observed in the cloud-bow direction, when usually only the aerosol reflectance contribution is measured and analysed for retrievals. 3MI will provide even more information thanks to the additional UV polarized channels that will help to constrain further the aerosol layer altitude and single scattering albedo of aerosol over clouds.



Aerosols over clouds

Average Optical Depth

(AOD at 865 nm)

over 3 months (JJA 2008)

Angström coefficient

over 3 months (JJA 2008)

*Figure17 : **Aerosol over clouds** retrievals from Parasol polarized measurements*

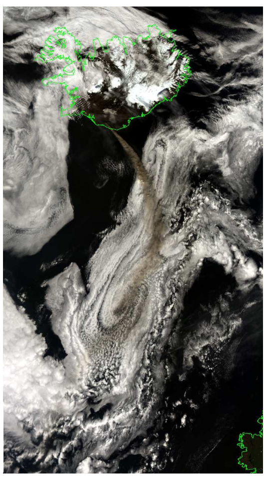
The 3 red areas on the AOD map correspond to blues on the Angström coefficient map, meaning large dust particles. Blues and greens on AOD correspond to oranges/reds on Angström coefficient meaning small particles.

Transport of biomass burning aerosols from southern Africa and pollution across the Pacific can be observed. [Credits Waquet 2011]

These new results are the first global maps of quantitative estimate of aerosol optical thickness over clouds.

When applied to the volcanic eruption in April 2010, the promising results on Fig. 18 show the ability to detect non spherical particles and to retrieve accurate optical depths over the plume despite heavy cloudy conditions in the area.

(a)



(b)

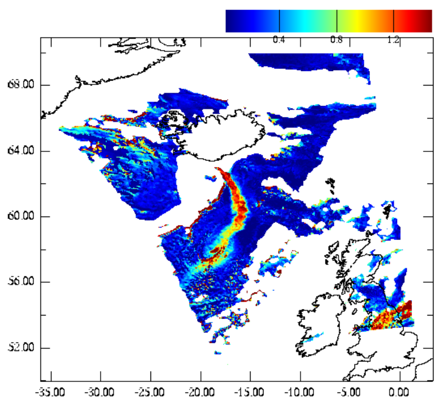


Figure 18-a is a MODIS composite image of the Eyjafjallajökull plume observed on 8/5/2010. Figure 18-b shows the AOD at 550 nm derived from PARASOL. Over the cloudy area, the algorithm uses the attenuation of the cloud polarized rainbow through the plume.
[Credits F. Waquet]

3.3.4 Polarization for Clouds

Although not the primary target objective of the 3MI mission, the polarization and multi-angle measurements provided will be used to derive some key cloud properties with much higher confidence than would be available from other planned sensors. Namely, cloud thermodynamic phase and liquid cloud particle size are critical elements for understanding cloud feedback and aerosols/clouds interactions and will be derived from 3MI to complement and strengthen microphysical properties derived from the primary cloud observation mission MetImage on EPS-SG.

Cloud thermodynamic phase is a critical parameters for cloud processes, precipitation onset and cloud radiative impact (Doutriaux et Quaas, 2004). Also, determination of cloud phase subsequently impacts the retrieval of cloud microphysical properties and any uncertainty in cloud phase determination impact the accuracy of cloud particle size quite dramatically.

Because of the remarkably reliable polarization signature of the rainbow POLDER has proved extremely useful to derive unbiased information on cloud phase (Goloub et al, 1999; Riedi et al, 2001; S. Zeng, 2011). Supplementing POLDER with MODIS spectral range, Riedi et al (2009) have further proposed a synergistic method to improve the confidence of cloud phase retrievals which in turn help improve the overall quality of derived cloud properties (cloud optical thickness, albedo, IWC/LWC).

Cloud droplet effective radius (DER) and liquid water path (LWP) are two key parameters for the quantitative assessment of cloud and aerosol interactions as well as cloud effects on the exchange of energy and water.

As demonstrated early by Bréon et al (2002), multi-angle and multi-spectral polarization observation provide a unique way of assessing with high accuracy the droplet size at the top of liquid clouds, an information which can in turn be used to better constraint our understanding of clouds/aerosols interactions. Platnick (2000) studied the impact of cloud droplet vertical profile on remote sensing of liquid cloud effective radius and Chang and Li (2002) presented an algorithm using multichannel measurements made at 3.7, 2.1, and 1.6 microns to retrieve a cloud DER vertical profile for improved cloud LWP estimation. Further, Bréon and Doutriaux (2005) examined differences between cloud effective radius derived respectively from POLDER multi-angle polarization and MODIS multi-spectral measurements and showed systematic differences that are still puzzling researchers. From these studies, there are clear evidences however that 3MI will bring again unprecedented observations to analyse and understand cloud droplet vertical profile variability at global scale, contributing to our advanced understanding of liquid cloud processes, particularly phase transition, precipitation onset and the various interactions between clouds and aerosols.

Due to the complexity of ice particles remote sensing of ice cloud still remain a very challenging problem. A number of microphysical model have been developed and used for ice cloud retrieval in the last decade (e.g., Macke et al., 1996; C.-Labonnote et al., 2001; Baran et al., 2001; Baum et al., 2005; Baran and C.-Labonnote, 2007). Unfortunately these models are significantly different from each other, making the uncertainties on ice clouds retrieval very large, and highly dependent of the model chosen in the retrieval scheme. A recent study from Zhang et al. (2009) demonstrated that the optical thickness retrievals based on the MODIS observations, but derived with different ice particle models, can be substantially different. They also shown that the ice particle models (through the asymmetry parameter) affect not only optical thickness retrieval but also the cloud radiative forcing calculations, stressing out the importance of a good representation of the ice particles scattering properties in the inversion scheme.

Thanks to its 3M capabilities, the POLDER instrument was able to significantly reduce the number of ice particle models that could catch the angular signature of reflected light from ice clouds. Indeed, the most interesting results that came out from these measurements is that perfect ice particles models (e.g., pure hexagonal model) are not able to explain the angular signature of both total and polarized radiance, but only heterogeneous model (e.g., with surface roughness, or impurities, Doutriaux-Boucher et al. 2000). However, because of its limited spectral range, the sensitivity of POLDER measurements to the ice particle size is almost negligible and limits its ability to fully constrain ice cloud radiative properties in a consistent way over the whole solar spectrum and infrared region. These limitations will be overcome by 3MI thanks to the spectral extension in the shortwave infrared and synergistic use of 3MI and MetImage data.

3.3.5 Additional skills

Besides aerosols and clouds POLDER has also demonstrated skills over land or ocean surfaces. Especially, measuring the directional signatures is essential for correcting directional effects which is critical for land surfaces monitoring with conventional spectral imagers, derivation of surface albedos and radiation budget computations.

As for the aerosols, polarization is also sensitive to constituents in the water and can provide interesting information on suspended matter in coastal areas.

POLDER can also derive water vapour accurately over reflective land surfaces.
For those applications more details are provided in annex.

3.4 Potential for improving the present concept

(As for good wines), the POLDER products have matured with time. Succeeding to the first class of algorithms ready in 1996 for POLDER 1, a second class was done for POLDER-2 and applied to PARASOL before the development of synergistic Parasol-Modis algorithms. But the wealth of 3M information allows for a second generation of algorithms that will abandon the Look Up Table approach to fully resolve the radiative transfer equations.

Those methods are currently under development [Dubovik et al., 2011; Hasekamp et al., 2011]. They already show very promising results when applied to 3M observations, either simulations, Aeronet or POLDER data. Hence there is already good evidence that the quality and number of parameters from the existing data sets can be significantly improved.

Above that, growth potential also exist at instrument level as will be shown later in the next section (§4).

3.5 POLDER conclusion

POLDER has been the first and is still the only polarimeter to provide Earth observations from space.

The instrument concept is simple, light, reliable and proven by a series of 3 instruments over 15 years.

With Parasol in the A-train along with Calipso active measurements and MODIS, POLDER results have been thoroughly compared to other missions and deemed valuable, not only for aerosols but also for clouds, radiation budget, land or ocean parameters.

Glory reflight report states that “the most recent studies by Dubovik et al. (2011), Hasekamp et al. (2011) and Tanré et al. (2011) have advanced POLDER to the forefront of passive aerosol retrieval from space”.

Still, further improvements on the processing and also on the instrument side seem feasible for an advanced instrument as proposed in the next section.

4 3MI as the solution for an advanced 3M instrument

4.1 3MI enhanced capabilities

4.1.1 Rationale

The results obtained from 3 missions of POLDER observations have clearly demonstrated the potential of 3M measurements to derive improved and innovative information on atmospheric constituents for operational monitoring of aerosols.

Nevertheless, POLDER suffered from a number of limitations which can be nowadays overcome thanks to technological improvements performed over the past 15 years.

Namely, POLDER capabilities were partially hampered by limited cloud screening performances and lack of information on non polarizing aerosols over land. Both aspects can now be improved significantly through affordable enhancements of the instrument. Three directions for improvement have been identified for 3MI (3M Imager) which are (i) the total spectral range, (ii) the spatial resolution and (iii) the swath of the instrument.

4.1.2 Rationale for spectral enhancement

First, a spectral extension toward shorter (UV) and longer (short-wave infrared, noted SWIR hereafter) wavelength will enable a much better characterization of both the coarse and fine mode fractions of the total optical thickness over land. This has been confirmed by theoretical studies performed by CNES/LOA to identify an optimal set of spectral channels in the framework of new generation retrieval algorithm relying on Bayesian optimization (Dubovik et al, 2011).

Especially, the SWIR channels will improve the sensitivity to large and non polarizing aerosols, allowing for the aerosol size distribution to be retrieved completely.

On the other hand, the additional UV observation of both total and polarized reflectance will allow to resolve the altitude vs single scattering albedo ambiguity while also providing a better description of aerosol absorption properties at these wavelengths. This will be contributing to a better speciation of aerosols including better distinction between (dust) aerosols and clouds for improved derivations of short-wave fluxes and radiative forcing computation.

By providing extended spectral capabilities in both the UV and short-wave infrared region, 3MI will also enable much better retrievals of surface albedos, again allowing complete estimate of short wave aerosol forcing.

Finally, with its unique combination of multi-angle, polarization and detailed SWIR measurements, 3MI will provide an ideally suited set of observations for unambiguous cloud phase determination which in turn will help improving the overall quality of derived aerosol and cloud properties (cloud optical thickness, microphysical properties, albedo, IWC/LWC).

4.1.3 Rationale for a better spatial resolution and large swath

The need for improved observation resolution is twofold and should not be confused with the requirement defined by users in terms of product resolution. Indeed, if a 10km resolution product maybe enough for users, higher resolution observations of the order of a few kilometres or better are needed to obtain the required quality at 10 km. Especially, subpixel cloud contamination and subpixel surface variability need to be resolved and accounted for to guarantee quality of the final product at coarser resolution. Recent studies by Marshak et al (2011) have shown that 50% of clear sky pixels are located 5km or closer to the nearest cloudy pixel which calls for an instrument resolution ideally of the order of the kilometre and not larger than 4 km. Current requirements for 3MI have been established to 2 km and 4km respectively for the VIS and SWIR channels since synergistic use of the MetImage observations will also help to identify sub-pixel contamination by small clouds.

Both the improved resolution and additional spectral channels will contribute to provide a better cloud detection and allow for retrievals to be performed at the aerosol/cloud frontier which is critical for understanding of their various interactions. Also, by allowing more retrievals to be performed, thanks to reduced cloud contamination by unresolved sub-pixel clouds, the product availability will increase which in turn should benefit monitoring applications.

Finally, a large swath in both along and across track directions will allow improve the daily global coverage (especially compared to PARASOL) while maintaining the possibility to perform multi-angle measurements over a large range of view zenith angle.

4.1.4 Summary of 3MI Requirements

Finally 3MI requirements (details in 3MI MRD) can be summarized as follows:

-large field of view of 114°

-10 to 14 directions of observation per ground pixel

-13 wavelengths and 8 with polarization (see Table 3)

-ground resolution from 4 km (VIS) to 8 km (SWIR)

-co-registration with MetImage providing subpixel information at 500 m resolution

Mission BAND	Central Wavelength (µm)	FWHM (µm)	Polarization	Primary Use	Priority
3MI-1[(1)]	**0.354**	0.01	Y	Absorbing aerosol	3
3MI-2[(1)]	**0.388**	0.01	Y		1
3MI-3	**0.443**	0.02	Y	Aerosol absorption and height indicators	1
3MI-4	**0.490**	0.02	Y	Aerosol, surface albedo, cloud reflectance, cloud optical depth	1
3MI-5	**0.555**	0.02	Y/N	Surface albedo	3
3MI-6	**0.670**	0.02	Y	Aerosol properties	1
3MI -7	**0.763**	0.01	N	Cloud height, absorption correction	2
3MI -8	**0.765**	0.04	N	Cloud height, absorption correction	2
3MI -9	**0.865**	0.04	Y	Vegetation, aerosol, clouds, surface features	1
3MI -10	**0.910**	0.02	N	H_2O absorption correction	1
3MI -11	**1.370**	0.04	Y/N	Cirrus clouds, water vapour imagery,	1
3MI -12	**1.650**	0.04	Y	Ground characterization	1
3MI -13	**2.130**	0.04	Y	Cloud microphysics at cloud top, Ground charact. for aerosol inversion	1

Table 3 : 3MI channels requirements [from EPS-SG MRD, annex 2]

4.2 3MI Expected products

The objective of the 3MI mission is to provide the following set of aerosol parameters in NRT to users :

- Aerosol optical depths for fine (accumulation), coarse and total modes at high horizontal resolution (less than 10 km)
- Aerosol particle size for accumulation, coarse and total modes.
- Aerosol type through Angström exponent, refractive index, non sphericity index.
- Aerosol height index
- Aerosol absorption

These parameters will be retrieved by constraining the aerosol normalized size distribution, particle concentration, fraction of non-spherical particles and the spectral variation of both real and imaginary part of the refractive index.

As an example, the figure 19 shows retrieval results obtained with the algorithm developed by Dubovik et al. (2011) when applied to 3MI synthetic observations corresponding to either dust aerosols over a bright surface, or biomass burning aerosols over vegetation. As can be seen from the figure, the algorithm can fully take advantage of 3M informations to retrieve aerosol properties even in the worst case scenario of a dust layer over bright surfaces. Especially, the very good performance of SSA retrievals will enable accurate speciation of aerosols and identification of sources from 3MI.

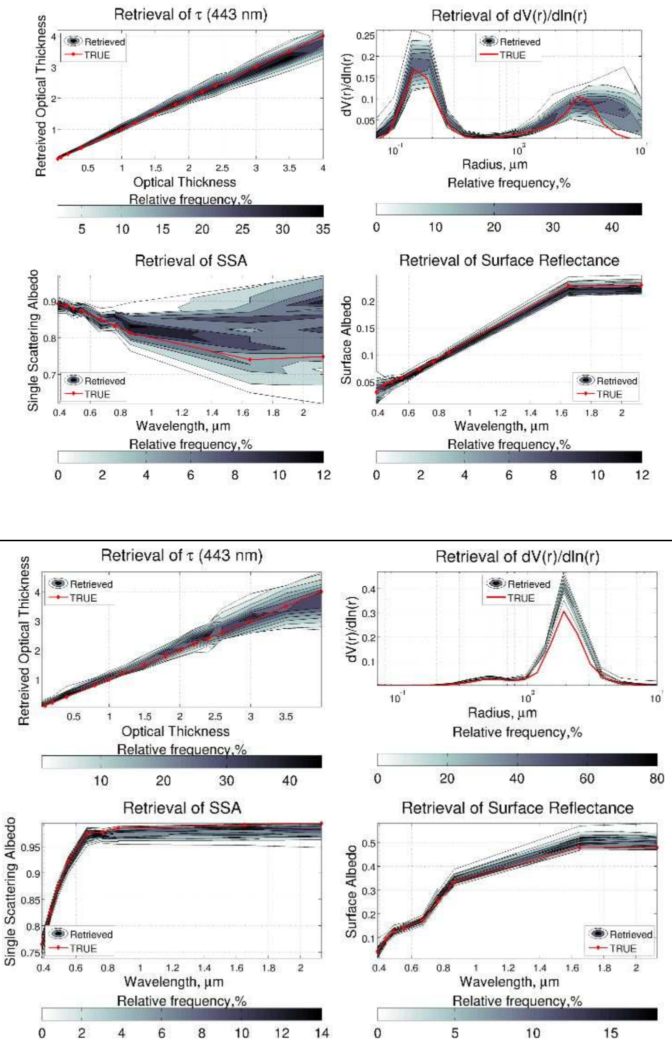


Figure 19: Examples of consistent retrieval of aerosols and surface properties by Dubovik et al. algorithm when applied to 3MI synthetic observations: biomass burning aerosols over vegetation (above), dust over bright target (below)

Comparison of the statistical distribution (grey shading) retrieved against the assumed value (truth in red) for the optical thickness at 443 nm with AOT ranging from 0.0 to 4.0 (top left), the size distribution (top right), the spectral variation of the single scattering albedo (lower left) and the surface reflectance (lower right) with an AOT of 1.0 at 443 nm.

[Credits LOA]

These fundamental aerosol properties will the be used to derive higher level products such as aerosol radiative forcing and heating rates.

When used as constraints these microphysical properties will allow air quality models to provide:

- Improved Air Quality Index
- PM : Aerosol Load mass for particles smaller than 2.5 µm (PM2.5) or 10 µm (PM10).

Additional parameters for secondary applications described in Annex 1 are also foreseen as described in 3MI MRD [Annex 2].

4.3 3MI instrument design

POLDER instrument concept which had been optimized in the 90's wrt POLDER mission specification was not necessarily the optimal solution wrt to enhanced 3MI specifications.

Consequently the main goal of the 3MI Phase 0 industrial studies conducted by CNES has been to fully reopen the search for an optimal instrument adjusted to answer 3MI requirements.

The outcome is that two separate industrial studies converged for 3MI on a "POLDER like" design augmented by an additional* optical head & detector dedicated to the SWIR range and by enhancement of a single filter wheel to support more filters. (*single or double depending on the number of detectors needed for SWIR)

So going from POLDER to 3MI does not require to change the instrument concept.

The procurement of a detector for the SWIR is critical to the implementation especially if 2 detectors instead of a single one have to be accommodated for the SWIR.

The UV, if restricted to388 nm, could be achieved with the same detector/optics as the VIS.

Altogether this results in a moderate increase of mass and power budgets.

Thus 3MI will still remain a "light" instrument with strong technical heritage limiting the development risk.

These results have been confirmed by ESA Phase A studies as reported in Annex 2.

5 Benefits from a dedicated instrument on EPS-SG for operational & long term monitoring of aerosols

Having recognized:

-the user needs for operational aerosol products,

-the state of the art aerosol remote sensing learned from A-train and the benefice from 3M observations,

-the lack of a dedicated aerosol instrument beyond A-train era,

-the lack of aerosol instrument on planned operational satellites,

-the POLDER background and growth potential from POLDER to an advanced 3MI instrument,
we propose now to consider the benefits from having the 3MI instrument to EPS-SG.

5.1 Timeframe, continuity, NRT

The first argument is the opportunity of EPS-SG **in time**.

EPS-SG is scheduled to be operational from 2020 to 2035 at least.

Science and applications around aerosols have matured over the past 20 years thanks to availability of more and more sophisticated observations.

But in the next decade we will come to the point where the lack of observations will limit further progression of both science and applications. “MODIS like” aerosol products will be derived from met-imagers with limited skills over land, over clouds and for aerosol speciation.

On the contrary, a 3MI instrument on EPS-SG would provide:

-dedicated aerosol products and unique observations for driving applications development

-continuity of observations at least for 15 Years

-NRT (Near Real Time) delivery with the warranty of EUMETSAT operational service as needed for GMES, NWP or Air Quality services.

5.2 Synergy

The second argument is **synergy** on EPS-SG.

Besides the full meteorological context, flying 3MI on EPS-SG would provide coincident measurements with Metimage, UVNS, IASI-NG and CERES.

As indicated in section 1.5 the aerosol information that is delivered by 3MI will help to improve the retrieval of especially tropospheric atmospheric trace gases from S5 UVNS, since aerosols affect the light path and therefore affect the detected trace gas columns. 3MI unique capabilities to deliver AOD and SSA as well as aerosol size information for fine and course mode, will allow significant improvements of tropospheric trace gas products (Leitão et al.2010).

Metimage/3MI will further increase the value of both sensors, as experienced for MODIS/Parasol. METimage finer resolution will help detection of subpixel inhomogeneities in 3MI. More spectral channels on METimage (for example UV channels for absorption or IRT channels for clouds) will complement the spectral capabilities of 3 MI. Synergistic 3MI/Metimage cloud detection, aerosol and cloud products could be implemented as well.

Synergy with CERES, as within A-train, is also essential for evaluating aerosol and cloud radiative impacts.

The major lesson learn from the A-train is "synergy". Like in an interference pattern, coincident measurements added together have a lot more strength for constraining models than isolated observations considered individually.

A high level of synergy will be offered by EPS-SG. Apart from active invaluable sensors, when considering also the second satellite the passive instrument suite on EPS-SG is comparable to the A-train.

It is worth highlighting also here the synergy with GEO observations from EUMETSAT.

Merging the "3M" observations from 3MI with temporal observations from GEOs (SEVIRI, FCI or others) would provide a highly valuable "4M" set observations for deriving hourly aerosol properties ultimately requested by NWP or AQ models. The next generation aerosol inversion scheme currently in preparation (Dubovik, Hasekamp) should be ready in 2020 for processing such large datasets.

5.3 Advanced but secured

3MI has the advantage of uniqueness with limited risk.

The measurement concept has been validated by the POLDER/Parasol missions.

The SWIR extension has been assessed by airborne measurements -both in France and in the US- and should be confirmed by APS. Polarization in the UV will be unique.

6 Conclusion

Climate and operational applications such as NWP or AQ strongly request to maintain current and enhance future satellite capabilities for measuring geographical and vertical distribution of aerosol amount and type, both over land and ocean, with controlled accuracy.

Beyond A-train era, only “MODIS class” conventional spectral imagers designed for meteorological purposes are currently planned. They have limited performance for aerosols, especially over land where applications are more demanding.

Growing attention is paid to polarization observations across the world. Indeed, when associated with Multi-spectral and Multi-directional capabilities, Multi-polarization observations provide the highest information content for retrieving aerosol optical and microphysical properties suitable for discrimination of aerosol type. Demonstration of the “3M” concept has been successfully achieved by the series of POLDER 1-2 and Parasol missions.

With limited impact on mass and power, the present POLDER design can be significantly enhanced with more spectral information and a better spatial resolution. The resulting **3MI** instrument, together with second generation of algorithms would provide an up to date new set of unique aerosol parameters.

Implementation of 3MI on EPS-SG would allow the adequate long term prospect and operational delivery of these products to users for developing their operational and climate applications.

Strong European expertise exists in instrumentation, algorithms as well as data processing centres. 3MI would capitalize on this heritage and skills.

Flying 3MI on EPS-SG would give Europe leadership in aerosol remote sensing for future decades.

7 Annex 1 : 3MI Additional skills

7.1 Water vapor

The distribution of water vapor concentrations is one of the essential climate variables defined by the World Meteorological Organization (WMO) (Rizzi et al, 2006). Moreover, operational meteorology relies on numerical weather prediction (NWP) models for which atmospheric humidity is a critical parameter.

Nowcasting and regional forecast models, like the Météo-France model AROME (Ducrocq et al, 2005) (from 2 to 3 days), have different needs, because of differences between the response time of the Earth system to changes in temperature, moisture, or the inertia of the layers interacting with the atmosphere. For this, the contribution of polar satellites can be important, if they are able to obtain measurement on the regional scale. Especially, there is a need for a better spatial resolution and a thicker spatial sampling compared to what can currently be achieved from infrared or microwave instruments. The regional forecast quality is therefore dependent on the water vapor measurements precision and on the small size of IFOV (for instance, the French regional model AROME has a horizontal resolution of 2.5 km).

POLDER, but also MERIS onboard ENVISAT as well as MODIS on NASA's Aqua and Terra satellites, provide capabilities to retrieve water vapor path (WVP) from near-infrared differential absorption techniques in the 910 and/or 940 nm water vapor band. Especially over cloud-free, reflective land surfaces and sun-glint, these estimates are highly accurate with an accuracy of better than 2 kg/m2 (or about 3-10% relative for a typical range of water vapor path) [Albert, et al., 2005; Bennartz and Fischer, 2001]. These observations are accurate enough for atmospheric correction purposes (e.g. [Li, et al., 2006]) as well as for data assimilation experiments. First data assimilation experiments using ECMWF's 4D-Var system are reported in [Bauer, 2009].

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7.2 Directionality for Surface BRDFs

Thanks to its unique design, the POLDER instrument has provided the most comprehensive

measurement of the directional signatures of land surface reflectance. These measurements have been used to quantify the variability of the BRDFs [Bacour et al., 2005], to analyse the capacity of model to reproduce the observed directional signatures [Maignan et al, 204] and to provide typical BRDFs for all major biomes [Bacour et al., 2006]. An unprecedented set of Hot Spot measurements (ie the directional signature of the reflectance close to backscattering) led to an improved understanding of the radiative transfer within the vegetation canopy [Bréon et al, 2002]. The BRDFs that are provided by POLDER are useful per se, but can also be used to correct the directional effects in the reflectance time series from other sensors such as MODIS [Maignan et al., 2008; Vermote et al, 2009]. Similarly the polarized-directional measurements from POLDER have been used to quantify the polarized properties of the land surface reflectances [Nadal and Bréon, 1999, Maignan et al., 2009].
Over the oceans, the directional signatures of the surface reflectances are directly related to the surface slope distribution, which is driven by wind speed and directions. POLDER measurements have been used for an unprecedented assessment of the ocean slope distribution in relation to the wind [Bréon and Henriot, 2006], which led to a better understanding of the air-water interaction at their interface [Munk, 2009]

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Bréon, F. M., and N. Henriot (2006), Spaceborne observations of ocean glint reflectance and modeling of wave slope distributions, J. Geophys. Res., 111, C06005, doi:10.1029/2005JC003343

Bréon, F.-M., F. Maignan, M. Leroy, and I. Grant (2002). Analysis of hot spot directional signatures measured from space. *J. Geophys. Res.*, **107**, 4282-4296.

7.3 Surface albedos

Land surface albedo quantifies the fraction of energy reflected by the surface of the Earth. As a corollary it then also determines the fraction of energy absorbed by the surface and transformed into heat or latent energy. Land surface albedo therefore is a key variable for characterizing the energy balance in the coupled surface-atmosphere system and constitutes an indispensable input quantity for soil-vegetation-atmosphere transfer models. Owing to strong feedback effects, the knowledge of surface albedo is also important for determining atmospheric conditions in the boundary layer. As Numerical Weather Prediction models become more sophisticated, it will become increasingly important to accurately describe the spatial and temporal albedo variations. On longer time scales, studies carried out with Global Circulation Models have revealed the sensitivity of climate with respect to changes in surface albedo.
The most relevant albedo quantity for applications related to the energy budget refers to the total short-wave broad-band interval comprising the visible and near infrared wavelength ranges where the solar down-welling radiation dominates. In more refined models the albedo values in the visible and near infrared broad-band ranges may also be exploited separately. In addition to serving as an intermediate product for deriving the broad-band albedo quantities, the spectral estimates contain a wealth of information about the physical state of the surface. This information can be used for a variety of purposes such as vegetation monitoring and land cover classification, which in turn also constitute important elements for setting up adequate surface modeling schemes.

A well-established approach for operational albedo determination is based on semi-empirical BRDF kernel models which have received a great deal of attention and effort from the optical remote sensing community in the last decades (Roujean et al., 1992; Barnsley et al., 1994; Wanner et al., 1995; Strahler, 1994; Hu et al., 1997). The approach is based on a decomposition of the bi-directional reflectance factor into a number of geometric kernel functions which are associated to the dominant light scattering processes, e.g. geometric and volumetric effects, a separation between the soil and vegetation, or the conjunction between media which are optically thick and thin (Lucht and Roujean, 2000). Both in situ measurements and numerical experiments have supported this assumption and the use of kernel-based models is widely accepted since they yield a pragmatic and cost-effective solution to the problem of BRDF inversion. Thanks to its instantaneous multiangle measurement capabilities, POLDER demonstrated clear advantage compared to other current generation sensors such as Seawifs, VEGETATION and MODIS because it provides higher constrain of kernel-based models (e.g., Leroy et al., 1997).

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7.4 ADMs for radiation budget

Top-of-Atmosphere (TOA) albedo is a fundamental parameter that controls both global and regional climate. Since satellites cannot directly measure flux instantaneously, one of the largest uncertainties in estimating TOA albedo from narrow field-of-view satellite instruments is the conversion of measured radiances to instantaneous albedo or flux. This is usually achieved through the use of Angular Distribution Models (ADMs) constructed from measured multidirectional radiances (Loeb et al, 2000).

Instruments such as the Cloud and the Earth's Radiant Energy System (CERES) or the Geostationary Earth Radiation Budget Experiment (GERB) are dedicated to this task (Loeb et al., 2003; Harries et al, 2005) but erroneous assumptions about the angular and spectral dependence of the radiation field can lead to errors in estimates of the planetary radiation budget.

Thanks to its instantaneous multiangle capabilities POLDER can retrieve TOA albedos relying solely on theoretical models of the atmosphere (Parol et al, 1999; Buriez et al, 2007) and can also contribute to a better determination of the empirical models (ADMs) to be used by other sensors.

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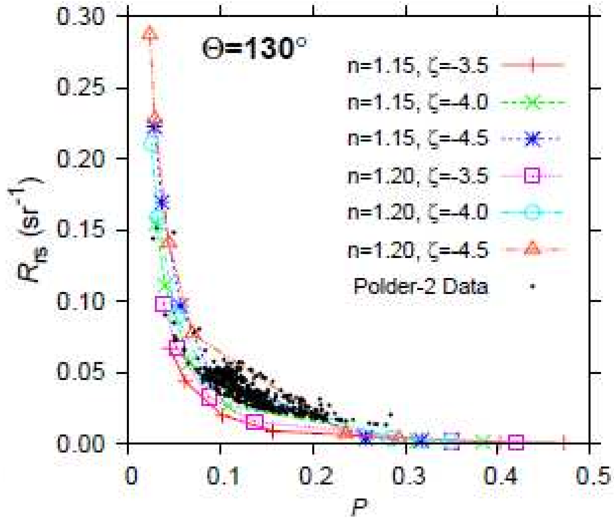
7.5 Polarization is also sensitive to constituents in the water

The biogeochemical characterization of marine particles suspended in sea water is of fundamental importance in many areas of ocean science. Previous studies based on theoretical calculations and field measurements have demonstrated the importance of the use of the polarized light field in the retrieval of the suspended marine particles properties (Ivanoff et al., 1961; Voss and Fry, 1984; Chowdhary et al., 2006; Chami et al., 2007). While the polarization of light is now extensively used in aerosol and cloud remote sensing studies, it has rarely been exploited from space borne observations of ocean color. This is partly explained by the fact that the polarized water leaving radiation (i) only represents a small fraction of the total radiation recorded by the satellite sensor over open ocean waters and (ii) is fairly insensitive to marine constituents in open ocean waters (Harmetl and Chami, 2008). However, over relatively bright areas, such as those encountered in coastal waters or during intense phytoplankton blooms, the polarized signal as detected from the POLarization and Directionality of the Earth's Reflectances (POLDER) sensor, can be exploitable from remote sensing (Loisel et al., 2008). The retrieved absolute values of the degree of polarization, its angular pattern, and its behavior with the scattering level are consistent with theory and field measurements [Fig. 20]. The availability of a polarized channel, especially in the red part of the spectrum which is much less affected by atmospheric scattering as well as by multiple scattering process occurring in the atmosphere-ocean system which depolarizes the signal, could therefore be used to obtain information on suspended marine particles properties.



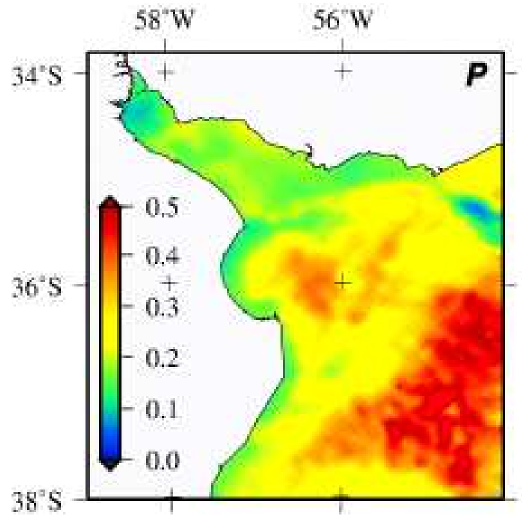


*Figure 20: **Left panel** Variation of the marine remote sensing reflectance, Rrs, as a function of the degree of polarization, P, for the value of the scattering angle of 130° for the Rio de la Plata estuary waters at 670 nm. The colored symbols represent data obtained from the radiative transfer simulations performed for different values of the refractive index (relative to water), n, and marine particle size distribution slope,ζ , as indicated. The black dots represent the data obtained from POLDER-2 observations. **Right panel** Map of the degree of polarization, P, of surface waters as estimated from POLDER2.[Credits H.Loisel]*

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8 Annex 2 : 3MI studies

8.1 Post-EPS Mission Requirements Document (MRD)

Refer to EUM/PEPS/REQ/06/0043 document for detailed 3MI specifications
http://www.eumetsat.int/Home/Main/Satellites/PostEPS/Resources/index.htm?l=en

8.2 ESA 3MI phase A study synthesis

ESA Contribution from Ilias Manolis / Jean-Loup Bézy – 11.08.2011

The 3MI instrument is a passive radiometer capable of measuring polarized Earth radiances under different viewing geometries across several spectral bands from the UV to the short-wave infrared (SWIR).

In order to facilitate the 'multi-viewing' type of measurements, a similar to POLDER measurement concept, i.e. a 2D imager in a pushbroom mode, is adopted. The multi-angular, multi-spectral and multi-polarization measurement is then performed by recording consecutive partially overlapping 2D images of the top of atmosphere (TOA) radiance over equally space points of the orbit. The measurement concept is visualised in figure 21 in the simplified case of only 2-views per target on Earth. 3MI will record every point on Earth under 14 viewing angles ranging at a minimum from -55° to +55°.

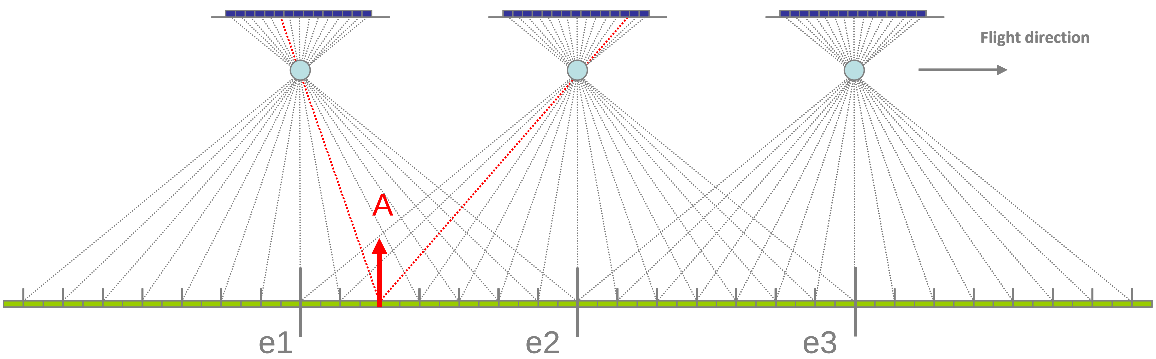


Figure 21 – Images are acquired over points e1, e2, & e3. In this example only two views per target on Earth (point A) are recorded [credits ESA]

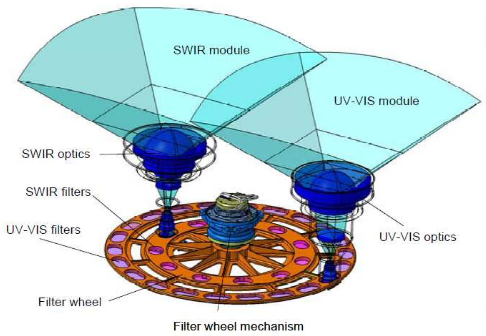
The large spectral range of the instrument dictates the use of several optical modules which are nevertheless of conceptually similar design and function. Still under trade-off, a minimum number of two (UVVIS + SWIR) and a maximum number of four (UV + VIS + SWIR1 + SWIR2) modules is currently under consideration for 3MI. While the split of the SWIR domain into two modules is dictated by the availability or not of a large format SWIR detector on time for the mission, the split of the UVVIS module into two modules is driven by the performance in the UV channels, the polarization sensitivity requirements and the FOV of the instrument.

Each module features a wide FOV dioptric telescope. The optical design is telecentric and typically deploys 10 optical elements, some of which including aspheric surfaces. High performance / low polarization anti-reflection (AR) coatings are deployed on all surfaces to meet the stringent straylight and polarization sensitivity requirements of the instrument. All optical heads feature a minimum FOV of ± 50.2°. From the MetOp-SG orbit this offers a swath of 2200 km and a full daily coverage of the globe with small gaps at equator.

Measurement of the different spectral channels and polarizations is performed sequentially in time and facilitated by a rotating filter wheel performing one revolution in less than 7s and which is placed between the optical heads and the focal plane assembly. The wheel features two concentric rings each accommodating the filter slots for the UVVIS and SWIR ranges respectively. Filter elements are a combination of Fabry-Perot (all dielectric) and blocking substrates (coloured glass).Polarisers are typically made of silver particles embedded in soda-lime glass.

Two-dimensional large format detectors are used on all modules. Charged Coupled Devices (CCD) and photovoltaic HgCdTe detectors hybridized on top of a CMOS Read-Out Integrated Circuit (ROIC) are proposed for the UVVIS and SWIR modules respectively. In order to reduce the dark current, the SWIR FPA is cooled down to 180K via means of passive cooling (radiator), and its temperature stabilized using controlled heater circuits.

The following figure shows an illustration of the 3MI concept as derived by the previous Phase 0 studies as well as the consolidated budgets and performance currently (PCR / Phase AB1)



Coverage	1 day
No. band	13
SSD	4 km
Swath width	2200 km
View angles	14 [from -55° to 55°]
SNR	200

No. of modules	2 to 4
Mass	40-60 Kg
Power	60-70 Watt
Volume	0.8x0.7x0.5 m^3
Date Rate	6.5 Mbps

Spectral bands

	Center nm	Width nm	Pol.
UV-VIS	354	10	Y
	388	20	Y
	443	20	Y
	490	20	Y
	555	20	Y
	670	20	Y
	754	20	N
	763	10	N
	865	40	Y
SWIR	910	20	N
	1370	40	Y
	1650	40	Y
	2130	40	Y

Figure 22 – (left) Phase 0 3MI concept. (right) Budgets and performance at PCR Phase AB1 [Credits ESA]

The 3MI instrument benefits largely from the heritage accumulated from the POLDER 1, 2 and 3 (PARASOL) instruments. The instrument concept relies on high technology readiness level compatible with the mission programmatic constraints. Several predevelopment activities have been initiated or will be initiated soon to demonstrate the ultimate performance of key elements of the instrument such as the polarization and spectral filters for some of the channels, the anti-reflection coatings, as well as the straylight performance of the full optical chain.

9 Annex 3 References

9.1 References on User requirements

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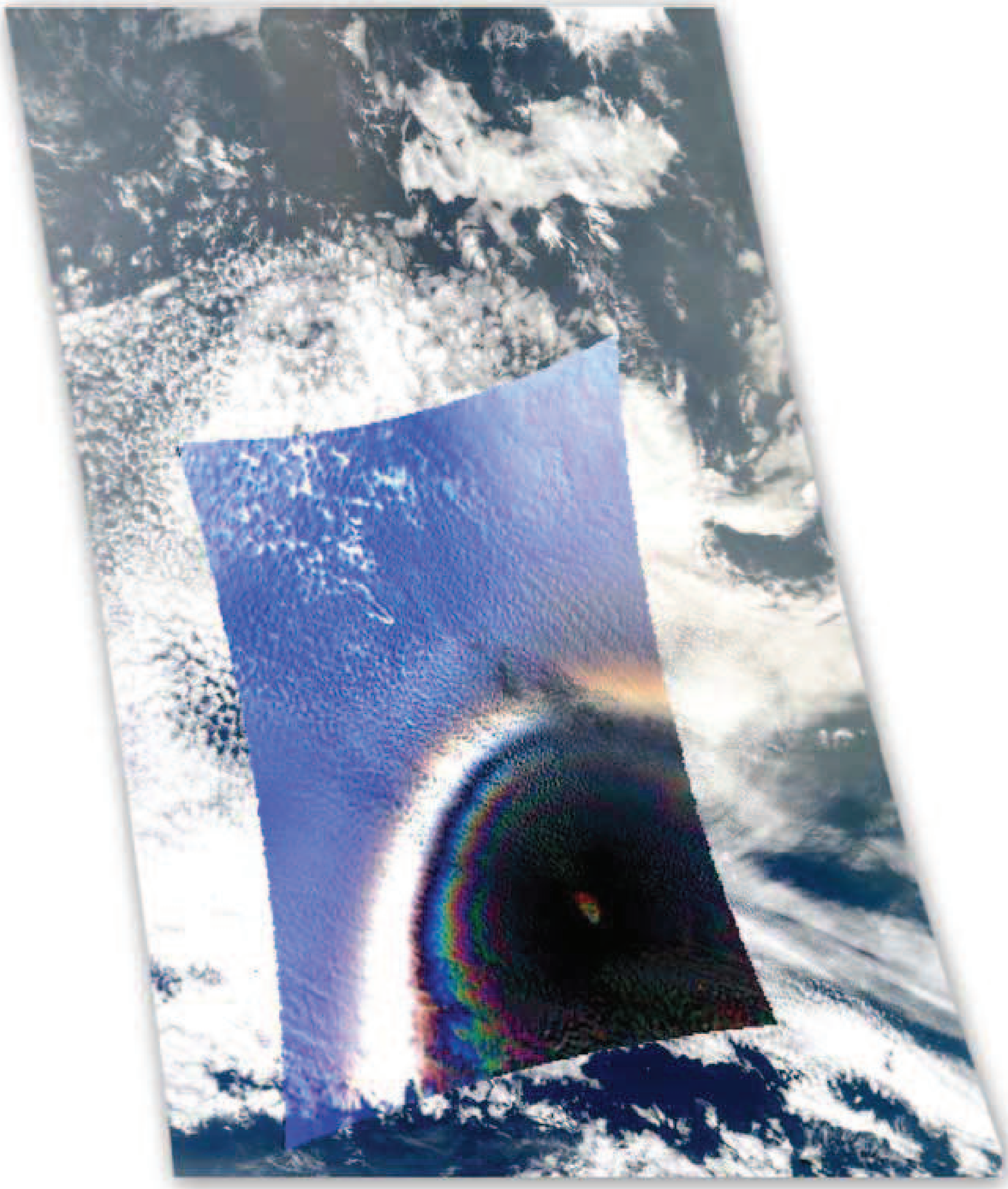

PARASOL/MODIS images prefiguring 3MI/MetImage on EPS-SG

During 5 years, POLDER/PARASOL and MODIS/AQUA flying in formation within the A-Train have provided a unique dataset prefiguring the 3MI/MetImage observations.

The background MODIS image is a true color composite showing the extended strato-cumulus desk off the coast of Namibia. Overlaid is a false color composite created from POLDER 490, 670 and 865 nm polarized channels.
This composite image exhibits the bright cloud bow characteristic of liquid clouds, partly extinguished by the presence of a cirrus cloud (dark) and aerosols (yellowish/orange) on the upper right side of the white bow.

The enhanced capabilities of 3MI compared to POLDER, combined with higher spatial resolution of MetImage will bring to operational mode retrieval capabilities which are currently at the forefront of research in aerosols and clouds remote sensing. These new operational products will contribute to improve multiple aspects of operational meteorology and forecasting, as well as climate and atmospheric composition monitoring and understanding.

The 3MI mission

for operational monitoring of aerosols from EPS-SG

Credits photos :

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